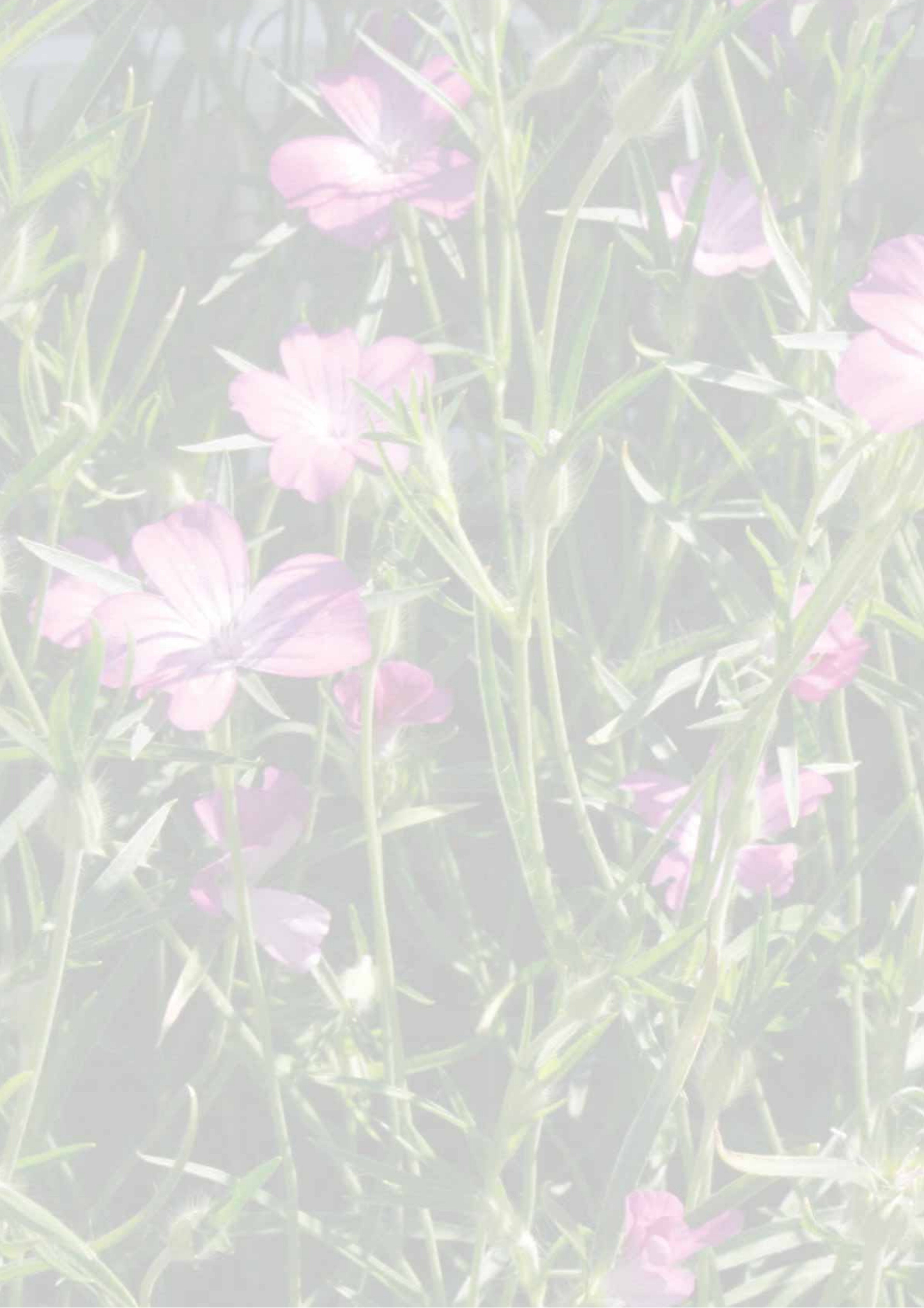
Connecting Global Priorities: Biodiversity and Human Health

A State of Knowledge Review

UNEP

Convention on Biological Diversity

World Health Organization



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CONOR KRETSCH

Forewords

Foreword by the Executive Secretary of the Convention on Biological Diversity

Biodiversity, ecosystems and the essential services that they deliver are central pillars for all life on the planet, including human life. They are sources of food and essential nutrients, medicines and medicinal compounds, fuel, energy, livelihoods and cultural and spiritual enrichment. They also contribute to the provision of clean water and air, and perform critical functions that range from the regulation of pests and disease to that of climate change and natural disasters. Each of these functions has direct and indirect consequences for our health and well-being, and each an important component of the epidemiological puzzle that confront our efforts to stem the tide of infectious and noncommunicable diseases.

The inexorable links between biodiversity, ecosystems, the provision of these benefits and human health are deeply entrenched in the Strategic Plan for Biodiversity, and reflected in its 2050 Vision: "Biodiversity is valued, conserved, restored and wisely used, maintaining ecosystem services, sustaining a healthy planet and delivering benefits essential for all people". They are central to our common agenda for sustainable development.

As science continues to unravel our understanding of the vital links between biodiversity, its persistent loss, global health and development, we become better equipped to develop robust, coherent and coordinated solutions that jointly reduce threats to human life and to the surrounding environment that sustains it. Increasing our knowledge of these complex relationships at all scales, and the influences by which they are mediated, enables us to develop effective solutions capable of strengthening ecosystem resilience and mitigating the forces that impede their ability to deliver life-supporting services. This state of knowledge review is a constructive step in this direction. I am especially grateful to the World Health Organization and all partners and experts who generously contributed to bring this to fruition.

We must ensure that interventions made in the name of biodiversity, health or other sectors do not compound but rather help to face the public health and conservation challenges posed by rising socio-demographic pressures, travel, trade and the transformation of once natural landscapes into intensive agricultural zones and urban and peri-urban habitats. We are all stakeholders in the pursuit of a healthier, more sustainable planet capable of meeting the growing needs of present and future generations. All sectors, policy-makers, scientists, educators, communities and citizens alike can – and must – contribute to the development of common solutions to the common threats that we face. Only in this way can we truly pave the road toward a more equitable, and truly sustainable, agenda in 2015 and beyond.

Braulio Ferreira de Souza Dias

Executive Secretary, Convention on Biological Diversity Assistant Secretary General of the United Nations

Foreword by the Director, Public Health, Environmental and Social Determinants of Health, World Health Organization

At WHO, we are aware of the growing body of evidence that biodiversity loss is happening at unprecedented rates. There is increasing recognition that this is a fundamental risk to the healthy and stable ecosystems that sustain all aspects of our societies.

Human health is not immune from this threat. All aspects of human wellbeing depend on ecosystem goods and services, which in turn depend on biodiversity. Biodiversity loss can destabilize ecosystems, promote outbreaks of infectious disease, and undermine development progress, nutrition security and protection from natural disasters.

Protecting public health from these risks lies outside of the traditional roles of the health sector. It relies on working with partners engaged in conservation, and the sustainable use and management of natural resources.

In this regard, WHO appreciates the leadership that the Secretariat of the Convention on Biological Diversity has shown in promoting the linkages between biodiversity and health.

The report synthesizes the available information on the most important inter-linkages; for example between biodiversity, ecosystem stability, and epidemic infectious diseases such as the Ebola virus; and the connection between biodiversity, nutritional diversity and health. It also covers the potential benefits of closer partnerships between conservation and health, from improved surveillance of infectious diseases in wildlife and human populations, to promoting access to green spaces to promote physical activity and mental health. Of course, it also highlights the many areas in which further research is needed.

We hope this joint report will be able to help policy makers to recognize the intrinsic value of biodiversity and its role as a critical foundation for sustainable development and human health and well-being.

In particular, we hope the report provides a useful reference for the Sustainable Development Goals and post-2015 development agenda, which represents an unique opportunity to promote integrated approaches to biodiversity and health by highlighting that biodiversity contributes to human well-being, and highlighting that biodiversity needs protection for development to be sustainable.

WHO looks forward to working jointly with our CBD colleagues, and the wider conservation community, to support this important agenda.

Dr. Maria Neira

Director, Public Health, Environmental and Social Determinants of Health, World Health Organization

Preface

Preface by the Chair of the Rockefeller-Lancet Commission on Planetary Health

The last 50 years have seen unprecedented improvements in human health, as measured by most conventional metrics. This human flourishing has, however, been at the cost of extensive degradation to the Earth's ecological and biogeochemical systems. The impacts of transformations to these systems; including accelerating climatic disruption, land degradation, growing water scarcity, fisheries degradation, pollution, and biodiversity loss; have already begun to negatively impact human health. Left unchecked these changes threaten to reverse the global health gains of the last several decades and will likely become the dominant threat to health over the next century. But there is also much cause for hope. The interconnected nature of people and the planet mean that solutions that benefit both the biosphere and human health lie within reach. Improving the evidence base of links between environment and health, identifying and communicating examples of co-benefits and building inter-disciplinary relationships across research themes are key challenges which must be addressed, to help build a post-2015 agenda where a healthy biosphere is recognised as a precondition for human health and prosperity.

In response to these challenges, The Rockefeller Foundation and The Lancet, have formed a Commission to review the scientific basis for linking human health to the underlying integrity of Earth's natural systems (The Commission on Planetary Health) and set out recommendations for action to the health community and policymakers working in sectors that influence health, development and the biosphere. The Commission has been underway since July 2014, and will conclude its work through the publication of a peer-reviewed Commission Report in The Lancet in July 2015.

The Commission welcomes this timely and important State of Knowledge Review from the Convention on Biological Diversity and the World Health Organization. The greatest challenge to protecting Planetary Health over the coming century is to develop the capability of human civilisations, to interpret, understand, and respond to the risks that we ourselves have created and this Review is a major advance in our understanding of these risks and the benefits of actions to reduce them.

Professor Sir Andy Haines

Chair of the Lancet-Rockefeller Foundation Commission on Planetary Health and Professor of Public Health and Professor of Primary Care at the London School of Hygiene and Tropical Medicine

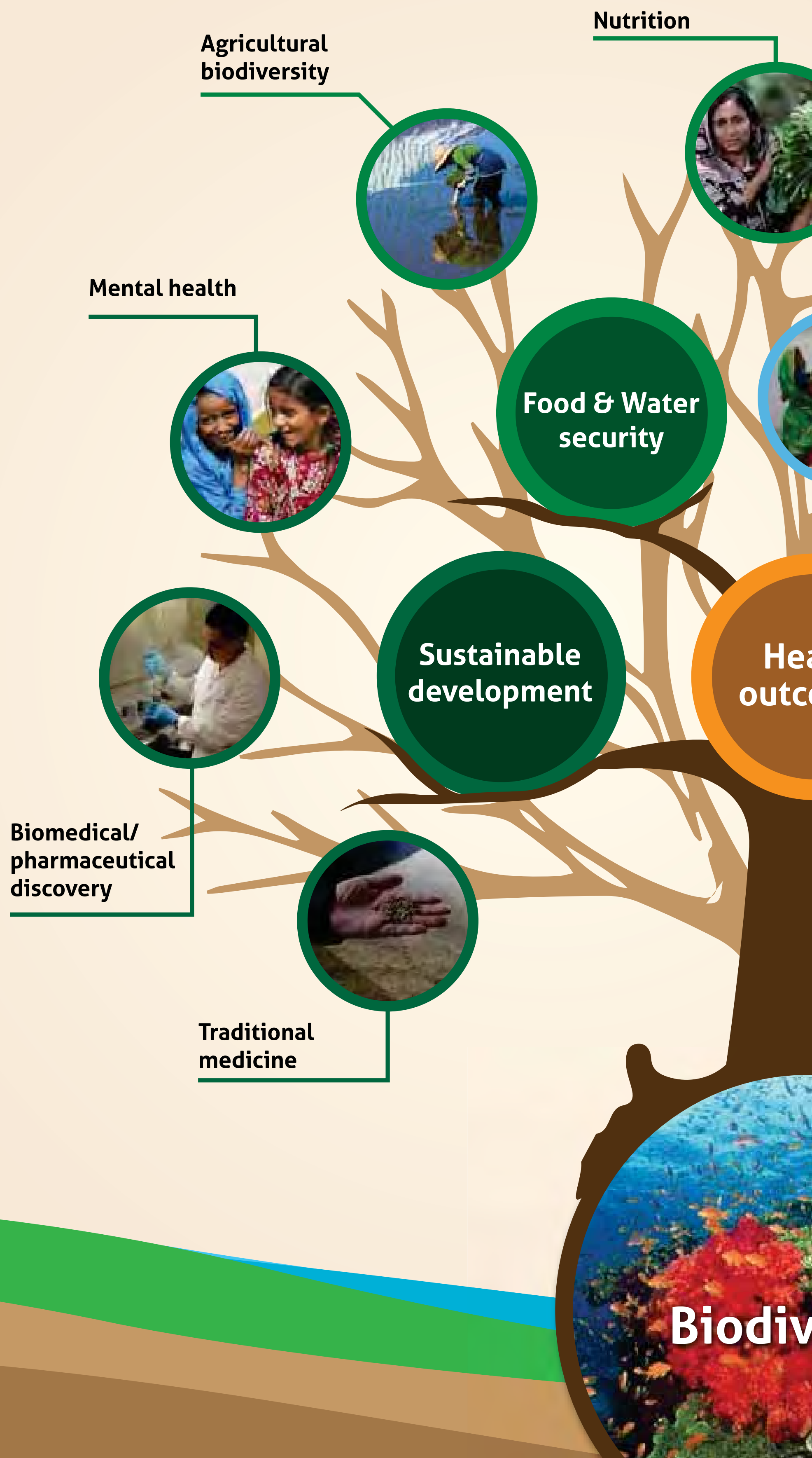
Biodiversity and

Health "is a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity".

Biological diversity (biodiversity) is "the variability among living organisms from all sources including, inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems."

Biodiversity underpins ecosystem functioning and the provision of goods and services that are essential to human health and well being.

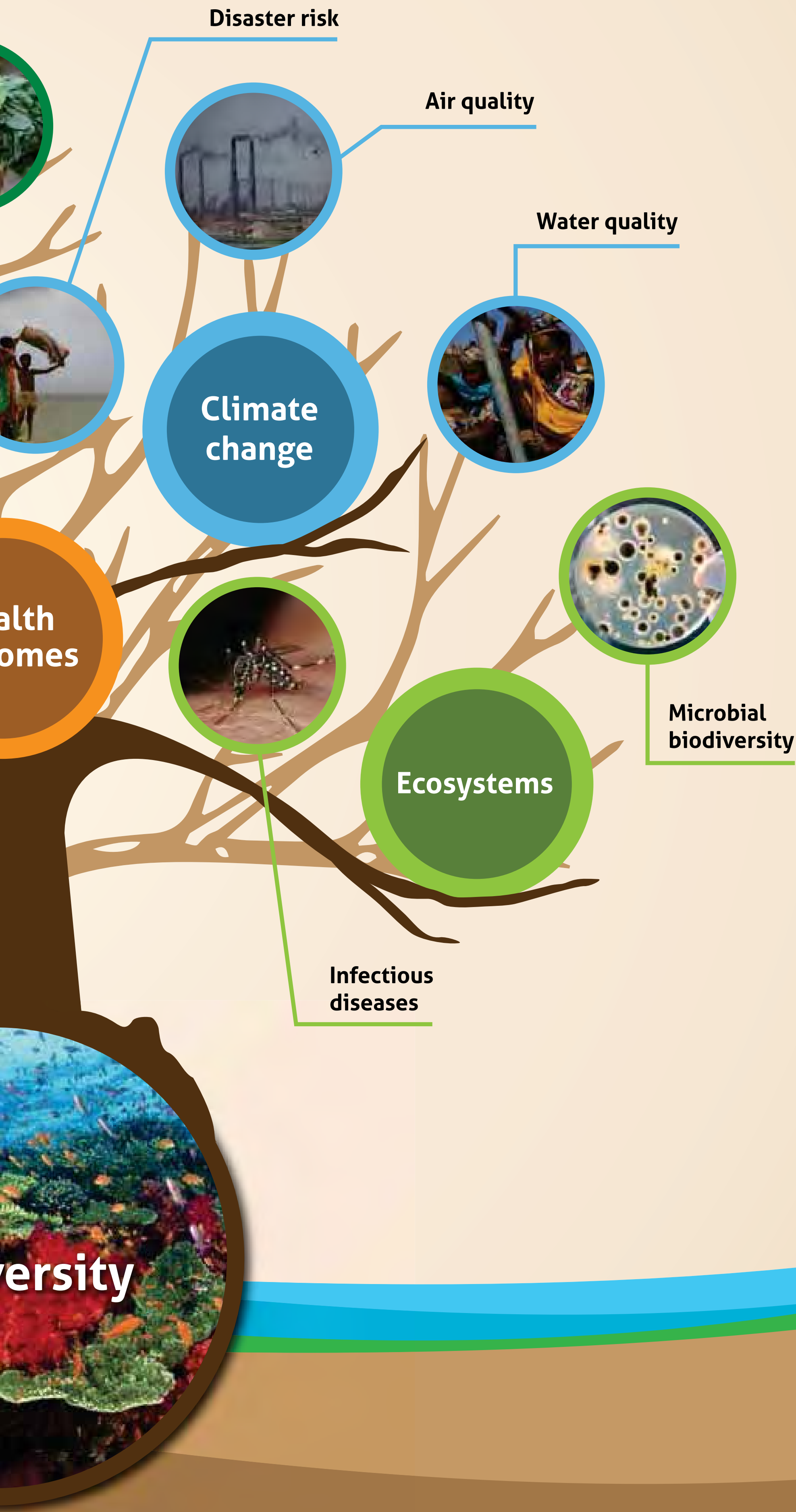
The links between **biodiversity and health** are manifested at various spatial and temporal scales. Biodiversity and human health, and the respective policies and activities, are interlinked in various ways.



World Health Organization

Convention on Biological Diversity

human health



Direct drivers of biodiversity loss include land-use change, habitat loss, over-exploitation, pollution, invasive species and climate change. Many of these drivers affect human health directly and through their impacts on biodiversity.

Women and men have different roles in the conservation and use of biodiversity and varying health impacts.

Human population health is determined, to a large extent, by social, economic and environmental factors.

The social and natural sciences are important contributors to biodiversity and health research and policy. Integrative approaches such as the Ecosystem Approach, Ecohealth and One Health unite different fields and require the development of mutual understanding and cooperation across disciplines.

GLEN BOWES

Executive Summary

INTRODUCTION

1. **Health "is a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity".** This is the definition of the World Health Organization. Health status has important social, economic, behavioural and environmental determinants and wide-ranging impacts. Typically health has been viewed largely in a human-only context. However, there is increasing recognition of the broader health concept that encompasses other species, our ecosystems and the integral ecological underpinnings of many drivers or protectors of health risks.

2. **Biological diversity (biodiversity) is "the variability among living organisms from all sources including, inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems."** This definition of the Convention on Biological Diversity (Article 2) reflects different levels of biodiversity (including genetic diversity, species and ecosystems) and the complexities of biotic and abiotic interactions. The attributes and interactions of biotic and abiotic components determine ecosystem processes and their properties. The effective management of ecosystems as part of comprehensive public health measures requires that these various complex linkages and interactions be identified and understood.

3. **Biodiversity underpins ecosystem functioning and the provision of goods and services that are essential to human health and well-being.** Ecosystems, including our food production systems, depend on a whole host of organisms: primary producers, herbivores, carnivores, decomposers, pollinators, pathogens, natural enemies of pests. Services provided by ecosystems include food, clean air and both the quantity and quality of fresh water, medicines, spiritual and cultural values, climate regulation, pest and disease regulation, and disaster risk reduction. Biodiversity is a key environmental determinant of human health; the conservation and the sustainable use of biodiversity can benefit human health by maintaining ecosystem services and by maintaining options for the future.

4. **The links between biodiversity and health are manifested at various spatial and temporal scales.** At a planetary scale, ecosystems and biodiversity play a critical role in determining the state of the Earth System, regulating its material and energy flows and its responses to abrupt and gradual change. At a more intimate level, the human microbiota – the symbiotic microbial communities present on our gut, skin, respiratory and urino-genital tracts, contribute to our nutrition, can help regulate our immune system, and prevent infections.

5. **Biodiversity and human health, and the respective policies and activities, are interlinked in various ways**. First, biodiversity gives rise to health benefits. For example, the variety of species and genotypes provide nutrients and medicines. Biodiversity also underpins ecosystem functioning which provides services such as water and air purification, pest and disease control and pollination. However, it can also be a source of pathogens leading to negative health outcomes. A second type of interaction arises from drivers of change that affect both biodiversity and health in parallel. For example, air and water pollution can lead to biodiversity loss and have direct impacts on health. A third type of interaction arises from the impacts of health sector interventions on biodiversity and of biodiversity-related interventions on human health. For example, the use of pharmaceuticals may lead to the release of active ingredients in the environment and damage species and ecosystems, which in turn may have negative knock-on effects on human health. Protected areas or hunting bans could deny access of local communities to bushmeat and other wild sourcs of food and medicines with negative impacts on health. Positive interactions of this type are also possible; for example the establishment of protected areas may protect water supplies with positive health benefits.

6. **Direct drivers of biodiversity loss include land-use change, habitat loss, over-exploitation, pollution, invasive species and climate change. Many of these drivers affect human health directly and through their impacts on biodiversity.** The continued decline of biodiversity, including loss or degradation of ecosystems, is reducing the ability of biodiversity and ecosystems to provide essential life-sustaining services and, in many cases, leads to negative outcomes for health and well-being. Ecosystem degradation may lead to both biodiversity loss and increased risk from infectious diseases. In turn, the indirect drivers of biodiversity loss are demographic change and large-scale social and economic processes. Social change and development trends (such as urbanization), poverty and gender also influence these drivers of change. Macro-economic policies and structures and public policies that provide perverse incentives or fail to incorporate the value of biodiversity often compound the dual threat to biodiversity and public health.

7. **Human population health is determined, to a large extent, by social, economic and environmental factors.** Social determinants of health include poverty, gender, sex, age, and rural versus urban areas. Vulnerable people, and groups (such as women and the poor) who tend to be more reliant on biodiversity and ecosystem services suffer disproportionately from biodiversity loss and have less access to social protection mechanisms (for example, access to healthcare). A social justice perspective is needed to address the various dimensions of equity in the biodiversity and health dynamic. Vulnerability and adaptation assessments are needed and should be tailored to the contexts of these populations.

8. **Women and men have different roles in the conservation and use of biodiversity and varying health impacts.** Access to, use, and management of biodiversity has differential gender health impacts shaped by respective cultural values and norms which in turn determine roles, responsibilities, obligations, benefits and rights. Institutional capacity and legal frameworks often inadequately reflect differential gender roles. There is also a lack of gender disaggregated data on biodiversity access, use and control and on the differential health impacts of biodiversity change.

9. **The social and natural sciences are important contributors to biodiversity and health research and policy. Integrative approaches, such as the ecosystem approach, ecohealth and One Health, unite different fields and require the development of mutual understanding and cooperation across disciplines.**

Multi-disciplinary research and approaches can provide valuable insights on the drivers of disease emergence and spread, contribute to identifying previous patterns of disease risk, and help predict future risks through the lens of social-ecological systems. Such challenges necessitate engagement of many stakeholders, including governments, civil society, and non-governmental and international organizations. Integrative approaches such as these make it possible to maximize resource efficiency as well as conservation, health and development outcomes. While their value is increasingly recognized for infectious disease prevention and control, their wider applications and benefits can also extend to other areas. For example, to the assessment of environmental health exposures and outcomes, better understanding of the health services provided by biodiversity, and of how anthropogenic changes to an ecosystem or biodiversity may influence disease risks.

WATER, AIR QUALITY AND HEALTH

ERIC SALES / ASIAN DEVELOPMENT BANK / FLICKR

Access to clean water is fundamental to human health and a priority for sustainable development. Yet, almost 1 billion people lack access to safe drinking water and 2 million annual deaths are attributable to unsafe water, sanitation and hygiene. Biodiversity and ecosystems play a major role in regulating the quantity and quality of water supply but are themselves degraded by pollution.

10. **Ecosystems provide clean water that underpin many aspects of human health.** All terrestrial and freshwater ecosystems play a role in underpinning the water cycle including regulating nutrient cycling and soil erosion. Many ecosystems can also play a role in managing pollution; the water purification services they provide underpin water quality. Mountain ecosystems are of particular significance in this regard. Many protected areas are established primarily to protect water supplies for people.

11. **Freshwater ecosystems, such as rivers, lakes and wetlands, face disproportionately high levels of threats due largely to demands on water and impacts of human activities such as dam construction and mining**. In some regions, up to 95% of wetlands have been lost and two-thirds of the world's largest rivers are now moderately to severely fragmented by dams and reservoirs. Freshwater species have declined at a rate greater than any other biome, with the sharpest decline in tropical freshwater biomes. More than one-third of the accessible renewable freshwater on earth is consumptively used for agriculture, industrial and domestic use, which often leads to chemical pollution of natural water sources. Other human activity, such as mining, can also lead to bioaccumulation and biomagnification.

12. **Impaired water quality results in significant social and economic costs.** Ecosystem degradation–for example through eutrophication caused by excessive nutrients–is a major cause of declines in water quality. Left untreated, poor quality water results in massive burdens on human health, with the most pronounced impacts on women, children and the poor. Maintaining or restoring healthy ecosystems (for example, through protected areas) is a cost-effective and sustainable way to improve water quality while also benefitting biodiversity.

13. **Water-related infrastructure has positive and negative impacts on biodiversity, livelihoods, and human health.** Altered waterways (e.g. dams, irrigation canals, urban drainage systems) can provide valuable benefits to human communities, but may be costly to build and maintain, and in some cases increase risks (e.g. flood risk from coastal wetlands degradation). They can also diminish native biodiversity and sometimes increase the incidence of water-borne or water-related illnesses such as schistosomiasis. Approaches integrating benefits of both physical/built and natural infrastructure can provide more sustainable and cost-effective solutions.


UNDP BANGLADESH / FLICKR

Air pollution is one of the most significant environmental health risks worldwide, responsible for seven million deaths in 2012. Bronchial asthma and chronic obstructive pulmonary disease are on the rise. Cardiovascular disease, immune disorders, various cancers, and disorders of the eye, ear, nose and throat are also affected by air pollution. Air pollution also affects biodiversity; it can reduce plant biodiversity and affect other ecosystem services, such as clean water and carbon storage.

14. **Ecosystems may affect air quality and have primarily beneficial outcomes for human health.** Ecosystems affect air quality in three main ways: (1) *Deposition* – ecosystems directly remove air pollution, through absorption or intake of gases through leaves, and through direct deposition of particulate matters on plant surfaces; (2) *Changes in meteorological patterns* – as ecosystems affect local temperature, precipitation, air flows, etc., they also affect air quality and pollutant emissions. By altering climate and shading buildings, ecosystems in cities alter energy use and consequent greenhouse gas emissions; (3) *Emissions* – many ecosystems emit volatile organic carbons (VOCs) including terpenes and arenes. While sometimes considered as pollutants, many natural VOCs play a critical role in atmospheric chemistry and air quality regulation. Ecosystems also release pollen, sometimes associated with acute respiratory problems. Burning of vegetation is also associated with significant pollution emissions.

15. **Components of biodiversity can be used as bioindicators of known human health stressors, as well as in air and water quality mapping, monitoring, and regulation.** Lichens are among the most widely utilized and well-developed indicators of air quality to date and are making headway as reliable indicators for air quality regulation. The shift in species is predictable and often correlates highly with deposition measures, making lichens an accurate, cost-effective tool for mapping and monitoring. Other groups of organisms with high local biological diversity (e.g., insects and other arthropods) have high potential as bioindicators because they have the capacity to provide more fine-grained information about the state of ecosystems; they are also relatively easy to survey. Water quality can be monitored through chemical analysis but long-term trends in freshwater ecosystems are perhaps better monitored using the diversity of aquatic organisms (e.g., benthic invertebrates) as proxy for water quality and ecosystem health.

BIODIVERSITY, FOOD PRODUCTION AND NUTRITION

BIOVERSITY

Agricultural productivity has increased substantially over the last 50 years yet some 800 million people are food insecure. It is estimated that by 2050 food production will have to feed over 9 billion people, many of whom will be wealthier and demand more food with proportionately more meat and dairy products that have greater ecological footprints.

Biodiversity underpins the productivity and resilience of agricultural and other ecosystems. However, land use change and agriculture are dominant causes of biodiversity loss.

16. **Biodiversity in and around agricultural production systems makes essential contributions to food security and health.** Biodiversity is the source of the *components of production* (crops, livestock, farmed fish), and the genetic diversity within these that ensures continuing *improvements* in food production, allows *adaptation* to current needs and ensures *adaptability* to future ones. Agricultural biodiversity is also essential for *agricultural production systems*, underpinning ecosystem services such as pollination, pest control, nutrient cycling, erosion control and water supply.

17. **The loss of diversity from agro-ecosystems is increasing the vulnerability and reducing the sustainability of many production systems and has had negative effects on human health.** While there have been significant increases in food production through the introduction of higher yielding uniform varieties and breeds, loss of genetic diversity in production systems through monocropping of uniform crop varieties or animal breeds has led to instances of large production losses and, in some cases, has had significantly negative health consequences. Loss of diversity has also resulted in the reduced provision of regulating and supporting ecosystem services, requiring additional chemical inputs and creating negative feedback loops.

18. **The use of chemical inputs, particularly pesticides, has had severe negative consequences for wildlife, human health and for agricultural biodiversity.** While the control of disease vectors such as malaria has generated health benefits, the use of pesticides, especially in agriculture, has led to serious environmental pollution, affected human health (25 million people per year suffer acute pesticide poisoning in developing countries) and caused the death of many non-target animals, plants and fish. The use of agricultural biodiversity to help cope with pests and diseases and to increase soil quality is a win-win option which produces benefits to human health and to biodiversity.

19. **Pollination is essential to food security generally and to the production of many of the most nutritious foods in particular**. Pollinators play a significant role in the production of approximately one third of global food supply. Pollination also affects the quantity, nutritional content, quality, and variety of foods available. Global declines of pollinator species diversity and in numbers of pollinators have critical implications for

food security, agricultural productivity and, potentially, human nutrition.

20. **Increasing sustainable production and meeting the challenges associated with climate change will require the increased use of agricultural biodiversity.** Climate change is already having an impact the nutritional quality and safety of food and increasing the vulnerability of food insecure individuals and households. The increased use of agricultural biodiversity will play an essential part in the adaptation and mitigation actions needed to cope with climate change and ensuring continued sustainable supplies of healthy food, providing adaptive capacity, diverse options to cope with future change and enhanced resilience in food production systems.


S. PADULOSI / BIOVERSITY

21. **Agricultural practices, which make improved use of agricultural biodiversity, have been identified and are being used around the world**. Their potential value needs to be more widely recognized and their adoption more strongly supported through research and support for appropriate policy and economic regimes, including appropriate support to small-scale producers. Inter-disciplinary analysis and cross-sectoral collaboration (among the agriculture, environment, health and nutrition communities) is essential to ensure the integration of biodiversity into policies, programmes and national and regional plans of action on food and nutrition security.

Malnutrition is the single largest contributor to the global burden of disease affecting citizens of every country in the world from the least developed to the most. Two billion people are estimated to be deficient in one or more micronutrients. At the same time, the consumption of poor-quality processed foods, together with low physical activity, has contributed to the dramatic emergence of obesity and associated chronic diseases.


B. VINCETI / BIOVERSITY

A diversity of species, varieties and breeds, as well as wild sources (fish, plants, bushmeat, insects and fungi) underpins dietary diversity and good nutrition. Variety-specific differences within staple crops can often be the difference between nutrient adequacy and nutrient deficiency in populations and individuals. Significant nutrient content differences in meat and milk among breeds of the same animal species have also been documented. Wildlife, from aquatic and terrestrial ecosystems, is a critical source of calories, protein and micronutrients like iron and zinc for more than a billion people. Fish provide more than 3 billion people with important sources of protein, vitamins and minerals.

22. **Access to wildlife in terrestrial, marine, and freshwater systems is critical to human nutrition, and global declines will present major public health challenges for resource-dependent human populations, particularly in low- and middle- income countries.** Even a single portion of local traditional animal-source foods may result in significantly increased clinical levels of energy, protein, vitamin A, vitamin B6/B12, vitamin D, vitamin E, riboflavin, iron, zinc, magnesium and fatty acids–thus reducing the risk of micronutrient deficiency. The use

of wild foods increases during the traditional 'hungry season' when crops are not yet ready for harvest, and during times of unexpected household shocks such as crop failure or illness. However, wildlife populations are in worldwide decline as a result of habitat destruction, over-exploitation, pollution and invasive species. Conservation strategies can therefore provide significant public health dividends.

23. **The harvesting and trade of wild edible plants and animals provides additional benefits but also risks.** The collection and trade of wild foods indirectly contributes to health and well-being by providing income for household needs, particularly in less developed countries. Aggregating across numerous local level studies, estimates of the annual value of the bushmeat trade alone in west and central Africa range between US$42 and 205 million (at 2000 values). This scale of economy poses important subsistence benefits. Hunting, butchering, consumption, global trade, and/or contact in markets with other species can also presents risks of transmission and spread of infectious disease

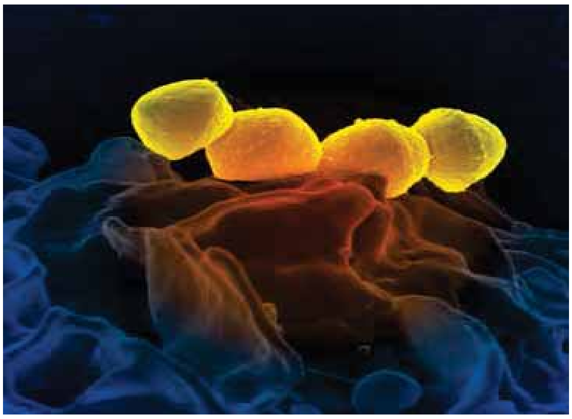
S. LANDERSZ / BIOVERSITY

24. **Food based approaches are needed to help combat malnutrition and promote health.** A healthy, balanced diet requires a variety of foods to supply the full range of nutrients needed (vitamins, minerals, individual amino acids and fatty acids, and other beneficial bioactive food components)

    While fortification and bio-fortification may be cost-effective solutions to address specific nutrient deficiencies (e.g. vitamin A and iron), they cannot provide the full range of nutrients needed. Food based approaches can be supported by a greater focus on nutrition and biological diversity in agricultural, food system and value chain programs and policies (compared to a dominant focus on a few staple crops), including by promoting traditional food systems and food cultures.

25. **Some dietary patterns that offer substantial health benefits could also reduce climate change and pressures on biodiversity.** The global dietary transition towards diets higher in refined sugars, refined fats, oils and meats, are increasing the environmental footprint of the food system and also increasing the incidence of type II diabetes, coronary heart disease and other chronic non-communicable diseases. Some traditional diets, such as the Mediterranean diet, and alternative vegetarian or near-vegetarian diets, if widely adopted, would reduce global agricultural greenhouse gas emissions, reduce land clearing and resultant species extinctions, and help prevent diet-related chronic non-communicable diseases.

MICROBIAL DIVERSITY AND NONCOMMUNICABLE DISEASES



NIAID / FLICKR

Non-communicable diseases are becoming prevalent in all parts of the world. Some NCDs including autoimmune diseases, type 1 diabetes, multiple sclerosis, allergic disorders, eczema, asthma, inflammatory bowel diseases and Crohn's disease may *be linked to depleted microbial diversity in the human microbiome.*

26. **Humans, like all complex plants and animals have microbiota without which they could not survive**. The human microbiome contains ten times more microorganisms than cells that comprise the human body. These occur *inter alia* on the skin, and in the gut, airways and urogenital tracts. The biodiversity of bacteria, viruses, fungi, archaea and protozoa of which microbes are comprised, and the interactions of microbes within the complex human microbiome, influence both the physiology of and susceptibility to disease and play an important role in the processes that link environmental changes and human health. The realization that humans are not merely "individuals", but rather complex ecosystems may be one of the major advances in our understanding of human health in recent years, with significant implications for both ecology and human health.

27. ***Environmental* microbial ecosystems are in constant dialogue and interchange with the human symbiotic ecosystems.** Microbes from the environment supplement and diversify the composition of the symbiotic microbial communities that we pick up from mothers and family, which in turn play significant roles from a physiological perspective. Our physiological requirements for microbial biodiversity are evolutionarily determined. In addition to supplementation of the symbiotic microbiota by organisms from the natural environment, the adaptability of the human microbiota (for example, to enable digestion of novel foods) depends upon acquiring organisms with the relevant capabilities, or genes encoding necessary enzymes from the environment by horizontal gene transfer. Therefore, we need appropriate contact with potential sources of genetic innovation and diversity, and our adaptability is threatened by loss of biodiversity in the gene reservoir of environmental microbes.

28. **Several categories of organism with which we co-evolved play a role in setting up the mechanisms that "police" and regulate the immune system**. In addition to the microbiota, some other organisms (the "Old Infections") that caused persistent infections or carrier states in hunter-gatherer communities were always present during human evolution, and so had to be tolerated by the immune system. Therefore they co-evolved roles in inducing the mechanisms that regulate the immune system, terminate immune activity when it is no longer needed, and block inappropriate attack on self (autoimmunity), allergens (allergic disorders) or gut contents (inflammatory bowel disease). Some of these immunoregulation-inducing organisms, for example a heavy load of helminths, can have detrimental effects on health, and so are eliminated by modern medicine in high-income settings. This increases the importance of the immunoregulatory role of microbiota and the microbial environment in high-income settings, where these categories of organism need to compensate for loss of these "Old Infections".

29. **Reduced contact of people with the natural environment and biodiversity and biodiversity loss in the wider environment leads to reduced diversity in the human microbiota, which itself can lead to immune dysfunction and disease.** The immune system needs an input of microbial diversity from the natural environment in order to establish the mechanisms that regulate it. When this regulation fails there may be immune responses to forbidden targets such as our own tissues (autoimmune diseases; type 1 diabetes, multiple sclerosis), harmless allergens and foods (allergic disorders, eczema, asthma, hay fever) or gut contents (inflammatory bowel diseases, ulcerative colitis, Crohn's disease). Urbanization and loss of access to green spaces are increasingly discussed in relation to these NCDs. Half of the world's population already lives in urban areas and this number is projected to increase markedly in the next half century, with the

most rapid increase in low- and middle-income countries. Combined, these findings suggest an important opportunity for cross-over between health promotion and education on biodiversity.

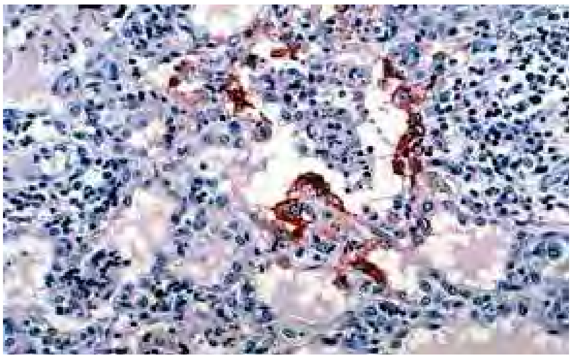
30. **Failing immunoregulatory mechanisms partly attributable to reduced contact with the natural environment and biodiversity lead to poor control of background inflammation**. In high-income urban settings, there is often continuous background inflammation even in the absence of a specific chronic inflammatory disorder. But persistently raised circulating levels of inflammatory mediators predispose to insulin resistance, metabolic syndrome, type 2 diabetes, obesity, cardiovascular disease and psychiatric disorders. Moreover, in high-income settings several cancers rise in parallel with the increases in chronic inflammatory disorders, because chronic inflammation drives mutation, and provides growth factors and mediators that stimulate tumour vascularisation and metastasis. We need to maintain the microbial biodiversity of the environment in order to drive essential regulation of the immune system.

31. **Understanding the factors that influence functional and compositional changes in the human microbiome can contribute to the development of therapies that address the gut microbiota and corresponding diseases.** Disturbances in the composition and diversity of the gut microbiota are associated with a wide range of immunological, gastrointestinal, metabolic and psychiatric disorders. The required microbial diversity is obtained from the individual's mother, from other people and from animals (farms, dogs) and the natural environment. The major influences on this diversity are antibiotics, diet, and diversity loss in the environment due to urbanisation and modern agricultural methods. We need to document the microbial biodiversity and the causes of diversity loss, preserve diversity, and identify the beneficial organisms and genes. These may be exploited for deliberate modification and diversification of the microbiota, which is emerging as an exciting new approach to prevention and cure of many human diseases.

32. **Innovative design of cities and dwellings might be able to increase exposure to the microbial biodiversity that our physiological systems have evolved to expect**. In high-income settings several very large studies reveal significant health benefits of living near to green spaces. The benefits are greatest for people of low socioeconomic status. Recent data suggest that the effect is not due primarily to exercise, and exposure to environmental microbial biodiversity is a plausible explanation. This provides a strong medical rationale for increased provision of green spaces in modern cities. It might be sufficient to supplement a few large green spaces with multiple small green spaces that deliver appropriate microbial diversity.

33. **Considering "microbial diversity" as an ecosystem service provider may contribute to bridging the chasm between ecology and medicine/immunology, by considering microbial diversity in public health and conservation strategies aimed at maximizing services obtained from ecosystems.** The relationships our individual bodies have with our microbiomes are a microcosm for the vital relationships our species shares with countless other organisms with which we share the planet.

INFECTIOUS DISEASES


CSIRO

Infectious diseases cause over one billion human infections per year, with millions of deaths each year globally. Extensive health and financial burden is seen from both established and emerging infectious diseases. Infectious diseases also affect plants and animals, which may pose threats to agriculture and water supplies with additional impacts on human health.

34. **Pathogens play a complex role in biodiversity and health, with benefits in some contexts and threats to biodiversity and human health in others.** The relationships between infectious pathogens and host species are complex; disease and microbial composition can serve vital regulating roles in one species or communities while having detrimental effects on others. Microbial dynamics, and their implications for biodiversity and health, are multifactorial; similarly, the role of biodiversity in pathogen maintenance and not fully understood.

35. **Human-caused changes in ecosystems, such as modified landscapes, intensive agriculture, and antimicrobial use, are increasing infectious disease transmission risks and impact.** Approximately two-thirds of known human infectious diseases are shared with animals, and the majority of recently emerging diseases are associated with wildlife. Vector-borne diseases also account for a large share of endemic diseases. Increasing anthropogenic activity is resulting in enhanced opportunities for contact at the human/animal/environment interface that is facilitating disease spread, and through changing vector abundance, composition, and/or distribution. Changes in land use and food production practices are among leading drivers of disease emergence in humans. At the same time, pathogen dynamics are changing. While pathogen evolution is a natural phenomenon, factors such as global travel, climate change, and use of antimicrobial agents are rapidly affecting pathogen movement, host ranges, and persistence and virulence. Beyond direct infection risks for human and animals, such changes also have implications for food security and medicine.

36. **Areas of high biodiversity may have high numbers of pathogens, yet biodiversity may serve as a protective factor for preventing transmission, and maintaining ecosystems may help reduce exposure to infectious agents.** While the absolute number of pathogens may be high in areas of high biodiversity, disease transmission to humans is highly determined by contact, and in some cases, biodiversity may serve to protect against pathogen exposure through host species competition and other regulating functions. Limiting human activity in biodiverse habitats may reduce human exposure to high-risk settings for zoonotic pathogens while serving to protect biodiversity.

37. **Infectious diseases threaten wild species as well as the people that depend on them.** The health burden of infectious diseases is not limited to humans and domestic species; infectious diseases pose threat to biodiversity conservation as well. Pathogen spill-over can occur from one wild species to another, potentially causing an outbreak if the species or population is susceptible to the pathogen; similarly, diseases of domestic animals and humans can also be infectious to wild species, as seen with the local extinctions of African Wild Dog populations following the introduction of rabies virus from domestic dogs. Ebola virus has also been recognized as causing severe declines in great ape populations, including the critically-endangered wild lowland gorilla troops. Past Ebola outbreaks in great apes have preceded

human outbreaks, suggesting a sentinel or predictive value of wildlife monitoring to aid in early detection or prevention of human infections. In addition to the direct potential morbidity and mortality threats from infectious diseases to the survival of wild populations, infection-related population declines may compromise health-benefitting ecosystem services that wildlife provide. For example, major declines recently seen from fungal infections associated with White Nose Syndrome in North American bats and chytrid in amphibians may affect the pest control functions that these animals provide.

38. **The rapidly growing number of invasive species cause significant impacts on human health, and this effect is expected to further increase in the future, due to synergistic effects of biological invasions and climate change.** Preventing and mitigating biological invasions is not only is important to protecting biodiversity, but can also protect human health. Through trade and travel, the number of invasive species is increasing globally as a consequence of the globalization of the economies, and the increase is expected to intensify in the future due to synergistic effects with climate change. Invasive species not only impact biodiversity, but also affect human health causing diseases or infections, exposing humans to bites and stings, causing allergic reactions, and facilitating the spread of pathogens.

MEDICINES: THE CONTRIBUTION OF BIODIVERSITY TO THE DEVELOPMENT OF PHARMACEUTICALS


GENEVIEVE ANDERSON

Many of the diseases that afflicted or killed most people a century ago are today largely curable or preventable today thanks to medicines, many of which are derived from biodiversity. Yet, in many instances, the very organisms that have given humanity vital insights into human diseases, or are the sources of human medications, are endangered with extinction because of human actions.

39. **Biodiversity has been an irreplaceable resource for the discovery of medicines and biomedical breakthroughs that have alleviated human suffering.** Drugs derived from natural products may perhaps be the most direct and concrete bond that many may find between biodiversity and medicine. Among the breakthroughs that dramatically improved human health in the twentieth century, antibiotics rank near the top. The penicillins as well as nine of the thirteen other major classes of antibiotics in use, derive from microorganisms. Between 1981 and 2010, 75% (78 of 104) of antibacterials newly approved by the USFDA can be traced back to natural product origins. Percentages of antivirals and antiparasitics derived from natural products approved during that same period are similar or higher. Reliance upon biodiversity for new drugs continues to this day in nearly every domain of medicine.

40. **For many of the most challenging health problems facing humanity today, we look to biodiversity for new treatments or insights into their cures.** Most of the medicinal potential of nature potential has yet to be tapped. Plants have been the single greatest source of natural product drugs to date, and although an estimated 400,000 plant species populate the earth, only a fraction of these have been studied for pharmacologic potential. One of the largest plant specimen banks, the natural products repository at the National Cancer Institute, contains ~60,000 specimens, for instance. Other realms of the living world, especially the microbial and marine, are only beginning to be studied and hold vast potential for new drugs given both their diversity and the medicines already discovered from them. Many species, potential sources of medicines are threatened by extinction.

41. **Greater even than what individual species offer to medicine through molecules they contain or traits they possess, an understanding of biodiversity and ecology yield irreplaceable insights into how life works that bear upon current epidemic diseases.** Consider the multiple pandemics that have resulted from antibiotic resistance. Human medicine tends to use a paradigm for treating infections unknown in nature which is treating one pathogen with one antibiotic. Most multicellular life (and a good share of single cellular life) produces compounds with antibiotic properties but never uses them in isolation. Infections are attacked, or more often prevented, through the secretion of several compounds at once.

TRADITIONAL MEDICINE

C. KRESTCH

Millions of people rely on traditional medicine that is dependent on biological resources, well functioning ecosystems and on the associated context specific knowledge of local health practitioners. In local communities, health practitioners trained in traditional and non–formal systems of medicine often play a crucial role in linking health-related knowledge to affordable healthcare delivery.

42. **Traditional medical knowledge spans various dimensions relating to medicines, food and nutrition, rituals, daily routines and customs. There is no single approach to traditional medical knowledge. Traditional knowledge is not restricted to any particular period in time, and constantly undergoes re-evaluation based on local contexts.** Some traditional medical systems are codified, and some even institutionalized. They range from highly developed ways of perception and understanding, classification systems (local-taxonomies) to metaphysical precepts. Links to geography, community, worldviews, biodiversity and ecosystems based on specific epistemologies make traditional health practices diverse and unique. By extension, level of expertise is heterogeneous and therefore internal validation methods differ substantially despite an underlying philosophical principle of interconnectedness of social and natural worlds.

43. **Medicinal and aromatic plants, the great majority of which are sourced from the wild, are used in traditional medicine and also in the pharmaceutical, cosmetic and food industries. The global use and trade in medicinal plants and other biological resources, including wildlife, is high and growing**. Plants used in traditional medicine are not only important in local health care, but are important to innovations in healthcare and associated international trade; they enter various commodity chains based on information gathered from their use in traditional medical pharmacopeia. Globally, an estimated 60,000 species are used for their medicinal, nutritional and aromatic properties, and every year more than 500,000 tons of material from such species are traded. It is estimated that the global trade in plants for medicinal purposes reaches a value of over 2,5 billion USD and is increasingly driven by industry demand.

44. **Threats to medicinal plants, animals and other medicinal resources are increasing.** Wild plant populations are declining- one in five species is estimated to be threatened with extinction in the wild. Animals (amphibians, reptiles, birds, mammals) used for food and medicine are more threatened than those not used. Overharvesting, habitat alteration, and climate change are among major drivers of declines in commercially important wild plant resources used for food and medicinal

purposes. These pose a threat both to the wild species and to the livelihoods of collectors, who often belong to the poorest social groups. There is a clear need to continue efforts at developing assessment methods and indicators for conservation and sustainable use.

45. **Sustainable use of medicinal resources can provide multiple benefits to biodiversity, livelihoods and human health, in particular, relating to their affordability, accessibility and cultural acceptability**. Sustainable medicinal resource management for both captive-breeding and wild-collection is crucial for the future of traditional medicine, that involves all stakeholders including conservationists, private healthcare sector, medical practitioners and its consumers. Appropriate market-based instruments to enable sustainable and responsible utilization of resources in traditional medicine are required. Value chains of traditional medicines can be simple and local or global and extremely complex. Some resources have one or a few specific uses while others are used in many different products and markets. In many cases the people who harvest these resources have little knowledge of the subsequent uses and values. Ensuring equitable economic returns to local communities by promoting value added activities at the local level could help to harness the knowledge of local communities on medicinal resources and promote their sustainable use.

46. **Sui generis models may need to be developed and applied to secure rights of indigenous peoples and local communities over traditional medical knowledge and related resources.** Traditional medical knowledge is often an inspiration for industrial R&D processes in bio-resource based sectors, necessitating mechanisms to secure appropriate attribution and sharing of rights and benefits with knowledge holders, as set out in the Nagoya Protocol on Access to genetic resources and equitable sharing of benefits arising from their commercial utilization. It would be beneficial to strengthen and promote existing tools, databases and registers and intellectual property rights that are sensitive to community values.

47. **Improving public health outcomes and achieving objectives of 'Health for All' and 'Good Health at Low Cost' should include traditional medical care and the development of appropriate integrative methodologies and safety standards within and across medical systems.** More than one-third of the population in many developing countries do not have access to modern healthcare, and are dependent on traditional medical systems. There is a high patronage of and dependence on traditional health practitioners to provide care to people with inadequate access to modern health infrastructure or with a preference for traditional systems. Pluralistic approaches that integrate natural resources and medical knowledge and are sensitive to local priorities and contexts can enable better health outcomes. This implies the need to develop cross-sectoral, cost-effective measures to test safety, efficacy and quality of traditional medicines, the integration of traditional healers in the healthcare system through appropriate accreditation practices and processes, cross-learning between different knowledge systems and disciplines through participatory, formal and informal learning processes to supplement current practices in a culturally sensitive way.

BIODIVERSITY AND MENTAL, PHYSICAL AND CULTURAL WELL-BEING

It is well established that biodiversity is a central component of many cultures and cultural traditions, and evidence that exposure to nature and more biodiverse environments can also provide mental and physical health benefits. Over half of the world's population lives in cities and that proportion is increasing. There is a rising trend for people, especially from poor communities, to be separated from nature and be deprived of the physical, physiological and psychological benefits that nature provides.

GLEN BOWES

48. **The interaction with nature – including domestic animals, and wild animals in wild settings – may contribute to treatments for depression, anxiety, and behavioural problems, including for children.** Exposure to nature is important to childhood development, and children who grow up with knowledge about the natural world and the importance of conservation may be more likely to conserve nature themselves as adults. Conversely, it has been stipulated that children in developed countries increasingly suffer from a "nature-deficit disorder", due to a reduction in the time spent playing outdoors as a result of increased use of technology and parental / societal fears for child safety. On the other hand, some research has suggested that some children, particularly those from urban areas, are fearful of spending time in certain natural habitats (woodland and wetland) owing to perceived threats from isolation, wild animals or the actions of other people.

49. **Exposure to green space may have positive impacts on mental health.** Depression accounts for 4.3% of the global burden of disease and is among the largest single causes of disability worldwide, particularly for women. Some studies of populations in developed countries have suggested that adults exposed to green space report fewer symptoms and a lower overall incidence of certain diseases than others, and that the relationship is strongest for mental illnesses such as depression, anxiety and stress. Similarly beneficial mental health impacts have been associated with greater exposure to microbial diversity. Other research has indicated that experience of nature can reduce recuperation times and improve recovery outcomes in hospital patients.

50. **Access to natural green space can increase levels of physical activity with benefits for health.** The benefits of physical activity may include reduced risk of several non-communicable diseases, as well as improved immune function. It may also provide mental health benefits, and facilitate social connections and independence. Among populations for which access to open countryside is limited, particularly those in poorer inner-urban areas of large cities, access to green spaces in the urban environment can encourage regular physical activity and improve life expectancy. It has also been suggested that health benefits may be more significantly attributable to enhanced exposure to environmental microbes in green spaces. There is evidence that biodiversity encourages use of urban green spaces. Efforts to develop biodiverse settings, including wildlife-rich gardens, can also boost physical activity in sedentary and vulnerable patients and residents. While, the potential that green space can offer for promoting and enhancing physical fitness is still not fully recognised, there is a growing interest in many countries to promote and enhance "green and blue infrastructure" (terrestrial and aquatic environments) within tourism, public health and environmental policies.

B. SHAPIT / BIOVERSITY

51. **Biodiversity is often central to cultures, cultural traditions and cultural well-being.** Species, habitats, ecosystems, and landscapes influence forms of music, language,

art, literature and dance. They form essential elements of food production systems, culinary traditions, traditional medicine, rituals, worldviews, attachments to place and community, and social systems. Use of the WHO Quality Of Life Assessment (devised to determine an individual's quality of life in the context of their culture and value systems) has shown that the environmental domain is an important part of the quality of life concept. Socio-ecological production landscapes (e.g. Satoyama in Japan) or conservation systems (e.g. sacred groves, ceremonial sites) or therapeutic landscapes (e.g. sacred healing sites), and related traditional knowledge practices can have therapeutic value and contribute to health and well-being.

52. **Significant changes to local biodiversity or ecosystem sustainability can have specific and unique impacts on local community health where the physical health of a community is directly influenced by or dependent upon ecosystem services, particularly regarding access to diverse food and medicinal species.** Indigenous and local communities often act as stewards of local living natural resources based on generations of accumulated traditional knowledge, including knowledge of agricultural biodiversity, and biodiversity that supports traditional medicinal knowledge. Where local traditions and cultural identity are closely associated with biodiversity and ecosystem services, declines in the availability and abundance of such resources can have a detrimental impact on community well-being, with implications for mental and physical health, social welfare and community cohesion.

53. **While many community-specific links between health, culture and biodiversity have been documented and measured, much of the evidence for a more universal relationship is relatively sparse beyond anecdotal accounts.** However, there is growing recognition of the role of biodiversity and ecosystem services in shaping broad perspectives of quality of life.

IMPACTS OF PHARMACEUTICAL PRODUCTS ON BIODIVERSITY AND CONSEQUENCES FOR HEALTH

Antibiotics and other pharmaceuticals are essential for human health and also play an important role in veterinary medicine. However, the release of active pharmaceutical ingredients into the environment can be harmful to biodiversity, with negative consequences for human health.

54. **The release of pharmaceuticals and Active Pharmaceutical Ingredients (APIs) into the environment can have an impact on biodiversity, ecosystems and ecosystem service delivery, and, may, in turn negatively impact human health.** A range of pharmaceuticals, including hormones, antibiotics, anti-depressants and antifungal agents have been detected in rivers and streams across the world. Most pharmaceuticals are designed to interact with a target (such as a specific receptor, enzyme, or biological process) in humans and animals to deliver the desired therapeutic effect. If these targets are present in organisms in the natural environment, exposure to some pharmaceuticals might be able to elicit effects in those organisms. Pharmaceuticals can also cause side effects in humans and it is possible that these and other side effects can also occur in organisms in the environment. During the life cycle of a pharmaceutical product, APIs may be released to the natural environment, including during the manufacturing process via human or domestic animal excretion into sewage systems, surface water or soils, when contaminated sewage sludge, sewage effluent or animal manure is applied to land. APIs may also be released into the soil environment when contaminated sewage sludge, sewage effluent or animal manure is applied to land. Veterinary pharmaceuticals may also be excreted directly to soils by pasture animals. Measures are needed to reduce this environmental contamination.

55. **Antibiotic and antimicrobial use can alter the composition and function of the**

human microbiome and limiting their use would provide biodiversity and health co-benefits. Antibiotic use can dramatically alter the composition and function of the human microbiome. Although much of the microbiome and its relationship to its host remains unexplored, already apparent is that changes to the variety and abundance of various microorganisms, as can occur with antibiotic use, may affect everything from the host's weight and the risk of contracting autoimmune disease, to susceptibility to infections. The microbiome may also be able to affect mood and behaviour. The use of antibacterial products and antibiotics may also be linked to the increase in chronic inflammatory disorders, including allergies such as asthma and eczema, because they reduce exposure to microbial agents that set up the regulation of the immune system. Limiting the use of antimicrobial agents could provide potential co-benefits for human health and biodiversity, reducing chronic inflammatory diseases through a healthy and more diverse human microbiota while also reducing the risk of emerging disease from antibiotic-resistant strains and the potential impacts of antibiotics on ecosystems more broadly.

56. **The inappropriate use of antibiotics in plants, animals, and humans has cultivated numerous highly resistant bacterial strains.** In some instances, resistant bacterial strains cannot be effectively treated with any currently available antibiotic. Promoting the responsible and prudent use of antibiotics and antimicrobials in human health, agricultural practices and food production systems can achieve public health and biodiversity co-benefits. Poorly managed industrial agricultural practices contribute to ecosystem degradation, air and water pollution and soil depletion and rely heavily on the inappropriate use of antibiotics for both therapeutic as well as prophylactic (growth promotion) use, which may lead to environmental dispersion of antimicrobial agents, antibiotic resistance, and reduced efficacy in subsequent use for medical or food production applications. From a health perspective, the use of antimicrobials and antibiotics may disrupt microbial composition, including the relationships between hosts and their symbiotic microbes, and lead to diseases. At the same time, antibiotic resistance in any environment can pose serious threats to public health. Aside from its potential to cultivate resistance, antibiotic use also carries the potential to disrupt symbiotic bacterial composition.

57. **Endocrine disrupting chemicals found in pharmaceuticals products and also in many household, food and consumer products have adverse effects on the health of terrestrial, freshwater and marine wildlife and human health.** The use of contraceptive hormones and veterinary growth hormones have been linked to endocrine disruption and reproductive dysfunction in wildlife. They also affect both male and female human reproduction, and have been linked to prostate cancer, neurological, endocrinological, thyroid, obesity, and cardiovascular problems. Biodiversity has also been a good monitor for some of these human health problems. In some cases, health specialists were alerted to the scale of a potential problem through changes originally recorded in wild fish populations.

58. **The inappropriate use of some non-steroidal anti-inflammatory drugs and other veterinary drugs threatens wildlife populations.** For example, in the 1980s, populations of three previously abundant vulture species in South Asia were reduced to near extinction due to the use in livestock of diclofenac, residues of which remained in the carcasses of treated animals. This led to negative impacts on human health through spread of diseases by feral dogs as access to carcasses increased, especially among communities who rely on vultures to consume their dead. Following bans on the use of diclofenac and its replacement by meloxicam, vulture population declines have slowed and some show signs of recovery in the region. Without proper risk assessment and regulation the marketing and

use of pharmaceuticals used for livestock may continue to pose threats to human and wildlife health.

GLOBAL CHANGE ADAPTATION TO CLIMATE CHANGE AND DISASTER RISK REDUCTION

AIRMAN 1ST CLASS CHERYL SANZI (USAF)

59. **Climate change is already negatively impacting on human health and these impacts are expected to intensify**. Direct effects of climate change on health may include stroke and dehydration associated with heat waves (in particular in urban areas), negative health consequences associated with reduced air quality and the spread of allergens Effects are also mediated through the impacts on ecosystems and biodiversity. Such effects may include decreased food production and changes in the spread of climate-sensitive waterborne and water-related, food-borne and vector-borne diseases. There may be synergistic effects of climate change, land use change, pollution invasive species and other drivers of change which can amplify impacts on both health and biodiversity.

60. **Climate change will not only affect agricultural production systems but also the nutritional content of foods and the distribution and availability of fisheries.** Changes in temperature and precipitation patterns will have complex effects, but the net effect on food production will be negative. While rising levels of atmospheric carbon, tend to increase productivity, they will lead to reduced concentrations of minerals such as zinc and iron in crops such as wheat and rice. With regard to marine fisheries, while there would be increased productivity at high latitudes there will be decreased productivity at low/mid latitudes, affecting poor developing countries.

61. **Disasters may be precipitated by impacts on critical ecosystems or the collapse of essential ecosystem services.** Disasters may include disease epidemics, flooding, storm, extreme weather, and wildfires. Some of these may be precipitated by ecosystem disruption. There is an increase in frequency and intensity of some climate-related extreme events. Ecosystem degradation can increase the vulnerability of human populations to such disasters. New environmental impacts often occur during and after an emergency with an increased demand for certain natural resources which can place additional stress on specific ecosystems (such as groundwater resources) and their functioning.

62. **Competition over access to ecosystem goods and services can contribute to, and become a cause of, conflict, with consequences that can negatively impact ecosystem goods and services in both the short- and long-term.** Greater recognition needs to be given to the potential positive role that conservation and ecosystem management can play in conflict prevention and resolution and peace building, while the converse also holds.

63. **The creation of disaster-resilient societies is increasingly tied to and dependent upon resilience in ecosystems, and sustainability and security in the flow and delivery of essential ecosystem goods and services** – not only those directly associated with resilience to immediate disaster impacts, but also those that normally support communities and wider society. Long-term health status is an important indicator of the resilience of a community – as a marker for capacity to overcome or adapt to health challenges and other social, environmental and economic pressures. Communities whose ability to overcome current challenges are affected by

ecosystem degradation at the time of a disaster event – natural or man-made – are likely to be significantly more vulnerable to disasters than communities with greater ecological security.

64. **Biodiversity helps to improve resilience of ecosystems, contributing to adaptation to climate change and moderating the impacts of disasters.** Ecosystem-based adaptation and mitigation strategies are needed to build the resilience of managed landscapes and jointly reduce the vulnerabilities of ecosystems and communities reliant upon them for their health, livelihoods and well-being. For example, Ecosystem-based approaches to flood-plain and coastal development can reduce human exposure to risks from flooding. Coral reefs are very effective in protecting against coastal hazards (reducing wave energy by 97%) and protect over 100 million people in this way from coastal storm surges. The conservation and use of genetic resources in agriculture, aquaculture and forestry is important to allow crops, trees, fish and livestock to adapt to climate change.

SUSTAINABLE CONSUMPTION AND PRODUCTION

65. **Increased pressure on the biosphere, driven by increasing human populations and per capita consumption threatens biodiversity and human health.** Biosphere integrity is threatened by a number of interacting drivers including climate change, land-use change, pollution and biodiversity loss. Global population is projected to increase to nine to ten billion by 2050, and may continue to increase this century. Greater investment in education of girls and women and improved access to contraceptives information and services can improve human health and well-being directly and also help to slow these trends, potentially reducing pressures on ecosystems. Under business as usual scenarios, increased per-capita consumption will lead to even greater increased pressures on the biosphere. Slowing these trends requires improvements in energy and resource use efficiency, including a decarbonization of energy supplies this century. These changes will need to be complemented by increased equality in access to and use of energy and other natural resources.

66. **Alternative scenarios to 2050, as well as practical experience, demonstrate that it is possible to secure food security and reduce poverty while also protecting biodiversity and addressing climate change and attain other human development goals, but that this requires transformational change.** Scenario analyses show that there are multiple plausible pathways to simultaneously achieve globally agreed goals. Common elements of these pathways include: reducing greenhouse gas emissions from energy and industry; increasing agricultural productivity and containing agricultural expansion to prevent further biodiversity loss and to avoid excessive greenhouse gas emissions from conversion of natural habitats; restoring degraded land, protecting critical habitats; managing biodiversity in agricultural landscapes; reducing nutrient and pesticide pollution and water use; reducing post harvest losses in agriculture and food waste by retailers and consumers as well as moderating the increase in meat consumption. Implementing these measures requires a package of actions including legal and policy frameworks, economic incentives, and public and stakeholder engagement. Coherence of policies and coordination across sectors are essential.

67. **Behavioural change is needed to improve human health and protect biodiversity.** Human behaviour, which is informed by differences in knowledge, values, social norms, power relationships, and practices is at the core of the interlinkages between health and biodiversity, including challenges related to food, water, disease, medicine, physical and mental well-being, adaptation and mitigation of climate change. There is a need to draw upon the social sciences to motivate choices consistent with health and biodiversity objectives and to develop new approaches

through, inter alia, better understanding of behavioural change, production and consumption patterns, policy development, and the use of non-market tools. The need for more effective communication, education and public awareness to be spread more widely through school systems and other channels and to devise communication and awareness strategies on biodiversity and health.

STRATEGIES FOR HEALTH AND BIODIVERSITY

68. **Health and biodiversity strategies could be developed with the aim of ensuring that the biodiversity and health linkages are widely recognized, valued, and reflected in national public health and biodiversity strategies, and in the programs, plans, and strategies of other relevant sectors, with the involvement of local communities.** The implementation of such strategies could be a joint responsibility of ministries of health, environment, and other relevant ministries responsible for the implementation of environmental health programs and national biodiversity strategies and action plans. Such strategies would need to be tailored to the needs and priorities of particular countries. Such strategies might include the following objectives:

    a. Promoting the health benefits provided by biodiversity for food security and nutrition, water supply, and other ecosystem services, pharmaceuticals and traditional medicines, mental health and physical and cultural well-being. In turn, this provides a rationale for the conservation and sustainable use of biodiversity as well as the fair and equitable sharing of benefits;

    b. Managing ecosystems to reduce the risks of infectious diseases, including zoonotic and vector-borne diseases, for example by avoiding ecosystem degradation, preventing invasive alien species, and limiting or controlling human-wildlife contact;

    c. Addressing drivers of environmental change (deforestation and other ecosystem loss and degradation and chemical pollution) that harm both biodiversity and human health, including direct health impacts and those mediated by biodiversity loss;

    d. Promoting lifestyles that might contribute jointly to positive health and biodiversity outcomes (for example, protecting traditional foods and food cultures, promoting dietary diversity)

    e. Addressing the unintended negative impacts of health interventions on biodiversity (for example, antibiotic resistance, contamination from pharmaceuticals), and incorporating ecosystem concerns into public health policies.

    f. Addressing the unintended negative impacts of biodiversity interventions on health (for example, effect of protected areas or hunting bans on access to food, medicinal plants).

    g. Adopting the One Health approach or other integrative approaches that consider connections between human, animal, and plant diseases and promotes cross-disciplinary synergies for health and biodiversity.

    h. Educating, engaging and mobilizing the public and the health sector, including professional health associations as potential, powerful advocates for the sustainable management of ecosystems. Mobilize organizations and individuals who can articulate the linkage and the enormous value proposition investments in sustainable ecosystem management provide to the social and economic health of communities;

    i. Monitoring, evaluating and forecasting progress toward the achievement of national, regional and global targets at regular intervals against evidence-based indicators, including threshold values for critical ecosystem services, such as the availability and access to food, water and medicines.

TOOLS, METRICS AND FURTHER RESEARCH

69. **Integration of biodiversity and human health concerns will require the use of common metrics and frameworks. Conventional** measures of health are often too limited in focus to adequately encompass the health benefits from biodiversity. Notwithstanding the broad WHO definition of health, traditional measures of health, such as disability adjusted life years (DALYs) and burden of disease, tend to have a more narrow focus on morbidity, mortality and disability, and fail to capture the full breadth of complex linkages between biodiversity and health. Alternative metrics defining health are needed to reflect the broad aspects of human health and well-being. Further, to increase collaboration across disciplines and sectors more attention could be paid to "translating" the meaning of key metrics to increase shared relevance. Similarly, frameworks provide a conceptual structure to build on for research, demonstration projects, policy and other purposes. Embracing a broad framework that aims to maximize the health of ecosystems and humans both could help the different disciplines and sectors work more collaboratively. The conceptual framework of the IPBES, building upon that articulated in the Millennium Ecosystem Assessment, is a framework that links biodiversity to human well-being, considering also institutions and drivers of change.

70. **The development of comparable tools–and maximizing the use of existing tools–to promote a common evidence base across sectors is needed.** Tools ranging from systematic assessment processes (for example, environmental impact assessments, strategic environmental assessments, risk assessments, and health impact assessments) to the systematic reviews of research findings, to standardized data collection forms to computerized modeling programs should also consider health-biodiversity linkages to manage future risks and safeguard ecosystem functioning while ensuring that social costs, including health impacts, associated with new measures and strategies do not outweigh potential benefits;

71. **The development of precautionary policies that place a value on ecosystem services to health, and make positive use of linkages between biodiversity and health are needed.** For example, for integrated disease surveillance in wildlife, livestock and human populations as a cost-effective measure to promote early detection and avoid the much greater damage and costs of disease outbreaks;

72. **Measuring health effects of ecosystem change considering established "exposure" threshold values helps highlight biodiversity-health-development linkages.** Mechanisms linking ecosystem change to health effects are varied. For many sub-fields, exposure thresholds or standards have been scientifically established that serve as trigger points *for taking action* to avoid or minimize disease or disability. For example, air quality standards exist for particle pollution, WHO has established minimum quantities of per capita water required to meet basic needs, and thresholds for food security define the quantity of food required to meet individual daily nutritional needs. Measuring the health effects of ecosystem change relative to established threshold values highlights how such change constitutes exposure – an important principle linking cause and disease or other health effects –and encourages action if thresholds are exceeded

73. **Economic valuation approaches linking ecosystem functioning and health that support decisions about resource allocation may appeal to a variety of stakeholders.** Many approaches enhance understanding of ecosystem functioning and human health linkages. Common on the health side are environmental hazard or risk factor analyses.

Others include identifying and reducing health disparities/inequities; focusing on environmental and socio-economic determinants of disease, and conducting health impact assessments. Conservation approaches include land-/seascape change modelling, vulnerability and adaptation assessments, linked health and environmental assessments and ecosystem service analyses.

74. **Further research is needed to elucidate some of the potential knowledge gaps on linkages between biodiversity and human health.** Examples of key questions include:
   a. What are the relationships between biodiversity, biodiversity change and infectious diseases? Specifically, what are the effects of species diversity, disturbance and human-wildlife contacts? What are the implications for spatial planning?

   b. What are the linkages between biodiversity (including biodiversity in the food production system), dietary diversity and health? Is there a relationship between dietary biodiversity and the composition and diversity of the human microbiome? What are good indicators of dietary biodiversity? What are the cumulative health impacts of ecosystem alteration?

THE SUSTAINABLE DEVELOPMENT GOALS AND POST-2015 SUSTAINABLE DEVELOPMENT AGENDA

75. **Health and biodiversity, and the linkages among them and with other elements of sustainable development must be well integrated into the post-2015 developmentw agenda.** The post-2015 development agenda provides a unique opportunity to advance the parallel goals of improving human health and protecting biodiversity. The Sustainable Development Goals will address various aspects of human well-being and be accompanied by targets and indicators. Specific biodiversity related targets and indicators should be integrated into Goals on food security and nutrition, water and health. The SDG framework should also provide for the enabling conditions for human health and for the conservation and sustainable use of biodiversity, and for the underlying drivers of both biodiversity loss and ill-health to be addressed. This implies Goals for improved governance, and institutions, at appropriate scales (from local to global), for the management of risks and the negotiation of trade-offs among stakeholder groups, where they exist, as well as for behavioural change.

76. **Ongoing evaluation of synergistic and antagonistic effects of complementary sustainable development goals and targets is needed.** This includes sustainable development goals and targets addressing health, food and freshwater security, climate change and biodiversity loss and evaluate the long-term impacts of trade-offs is needed; such as the trade-off and short-term gains from intensive and unsustainable agricultural production, against longer-term nutritional security. For example, the impacts of unsustainable agricultural practices that may exacerbate climatic pressures may also lead to greater food insecurity, particularly among poor and vulnerable populations, by negatively influencing its availability, accessibility, utilization and sustainability.

77. **Health is our most basic human right and therefore one of the most important indicators of sustainable development. At the same time, the conservation and sustainable use of biodiversity is imperative for the continued functioning of ecosystems at all scales, and for the delivery of ecosystem services that are essential for human health**. There are many opportunities for synergistic approaches that promote both biodiversity conservation and the health of humans. However, in some cases there must be trade-offs among these objectives. Indeed, because of the complexity of interactions among the components of biodiversity at various tropical levels (including parasites and symbionts), and

across ecosystems at various scales (from the planetary-scale biomes to human-microbial interactions), positive, negative and neutral links are quite likely to occur simultaneously. An enhanced understanding of health–biodiversity relationships will allow for the adjustment of interventions in both sectors, with a view to promoting human well-being over the long-term.

PART I

Concepts, Themes & Directions

CONOR KRETSCH

1. Introduction to the State of Knowledge Review

The right to health is well established as a fundamental right of every human being.[1] Biodiversity is at the heart of the intricate web of life on earth and the processes essential to its survival. Our planet's biological resources are not only shaped by natural evolutionary processes but are also increasingly transformed by anthropogenic activity, population pressures and globalizing tendencies. When human activity threatens these resources, or the complex ecosystems of which they are a part, it poses potential risks to millions of people whose livelihoods, health and well-being are sustained by them. The increasingly complex global health challenges that we face, including poverty, malnutrition, infectious diseases and the growing burden of noncommunicable diseases (NCDs), are more intimately tied than ever to the complex interactions between ecosystems, people and socioeconomic processes. These considerations are also at the heart of the post-2015 Development Agenda and the Sustainable Development Goals (SDGs).

The dual challenges of biodiversity loss and rising global health burdens are not only multifaceted and complex; they also transcend sectoral, disciplinary and cultural boundaries, and demand far-reaching, coherent and collaborative solutions. One of the widely acknowledged shortcomings of the Millennium Development Goals (MDGs) and targets (the precursors of the SDGs) was the lack of cross-sectoral integration among social, economic and environmental goals, targets and priorities (Haines et al. 2012). Opposing trends have been reported among the key indicators for the MDGs, with many negative trends for environmental indicators, including biodiversity (CBD 2014; Haines et al. 2012; WHO 2015).

The World Health Organization (WHO) and the Secretariat of the Convention on Biological Diversity (CBD) are working together to address these challenges.[2] This State of Knowledge Review assembles expertise and insights from numerous researchers, practitioners, policy-makers

[1] The right to health is established as a fundamental right of every human being in Article 1 of the World Health Organization Constitution (http://www.who.int/governance/eb/who_constitution_en.pdf). This was the first international instrument to enshrine the "right to health" as the "enjoyment of the highest attainable standard of health", also reflected in the Universal Declaration of Human Rights in 1948. The right to health is understood as an inclusive right that extends beyond health care to include the underlying determinants of health, such as access to water and food, essential medicines, etc.

[2] The World Health Organization and the Convention on Biological Diversity have been cooperating to promote greater awareness about, and action on, the interlinkages between human health and biodiversity by convening experts from relevant organizations, joint publications and organizing regional capacity-building workshops for experts from the biodiversity and health sectors in the Americas and Africa (Romanelli et al. 2014). The Conference of the Parties to the Convention on Biological Diversity has adopted a number of decisions in this regard (CBD 2010, 2012, 2014).

and experts from the fields of biodiversity conservation, public health, agriculture, nutrition, epidemiology, immunology, and others to do the following:

- Provide an overview of the scientific evidence for linkages between biodiversity and human health in a number of key thematic areas;

- Contribute to a broader understanding of the importance of biodiversity to human health in the evolving context of the SDGs and post-2015 Development Agenda, as well as the Strategic Plan for Biodiversity 2011–2020 (see Box 1);

- Facilitate cross-sectoral, interdisciplinary and transdisciplinary approaches to health and biodiversity conservation, and promote cooperation between different sectors and actors in an effort to mainstream biodiversity in national health strategies and mainstream health in biodiversity strategies;

Box 1: Strategic Plan for Biodiversity 2011–2020

The Strategic Plan for Biodiversity 2011–2020 and its twenty Aichi Targets provide an agreed overarching framework for action on biodiversity, and a foundation for sustainable development for all stakeholders, including agencies across the United Nations (UN) system. The Strategic Plan was adopted at the tenth meeting of the Conference of the Parties to the Convention on Biological Diversity and has been recognized or supported by the governing bodies of other biodiversity-related conventions, including the Convention on International Trade in Endangered Species of Wild Fauna and Flora, the Convention on the Conservation of Migratory Species of Wild Animals, the Convention on Wetlands of International Importance, the International Treaty on Plant Genetic Resources for Food and Agriculture, the World Heritage Convention, as well as the UN General Assembly.

Governments at Rio+20 affirmed the importance of the Strategic Plan for Biodiversity 2011–2020 and achieving the Aichi Biodiversity Targets, emphasizing the role that the Strategic Plan plays for the UN system, the international community and civil society worldwide to achieve the world we want. It is primarily implemented by countries through national biodiversity strategies and action plans, with Parties encouraged to set their own national targets within the framework of the Aichi Biodiversity Targets. The UN General Assembly has encouraged Parties and all stakeholders, institutions and organizations concerned to consider the Strategic Plan for Biodiversity 2011–2020 and the Aichi Biodiversity Targets in the elaboration of the post-2015 UN Development Agenda, taking into account the three dimensions of sustainable development.

The Strategic Plan for Biodiversity 2011–2020 includes a vision for 2050, five strategic goals and twenty Aichi Biodiversity Targets, mostly to be achieved by 2020. The 2050 Vision stresses the role of biodiversity for human well-being: "biodiversity to be valued, conserved, restored and wisely used, maintaining ecosystem services, sustaining a healthy planet and delivering benefits essential for all people". The five goals include: to protect nature (Goal C), to maximize the benefits for all people (Goal D), to reduce pressures on biodiversity (Goal B), to address the underlying causes of loss (Goal A), and to provide for enabling activities (Goal E). Under Goal D, Target 14 specifically refers to human health: "By 2020, ecosystems that provide essential services, including services related to water, and contribute to health, livelihoods and well-being, are restored and safeguarded, taking into account the needs of women, indigenous and local communities, and the poor and vulnerable."

The Strategic Plan also includes means of implementation, monitoring, review and evaluation, as well as support mechanisms (strategy for resource mobilization, capacity building, technical and scientific cooperation).

- Provide some of the basic tools necessary to investigate how biodiversity may influence health status or health outcomes, for given projects, policies or plans at varying levels (i.e. from community to the national, regional and global levels).

This work is aimed primarily at policy-makers, practitioners and researchers working in the fields of biodiversity conservation, public health, development, agricultural and other relevant sectors. Its findings suggest that greater interdisciplinary and cross-sectoral collaboration is essential for the development of more coordinated and coherent policies aimed at addressing the tripartite challenge of biodiversity loss, the global burden of ill-health and development. Interdisciplinary scientific investigation and approaches are critical to meeting these challenges. This volume demonstrates the need to foster greater synergy across scientific disciplines, social sciences and humanities, with more coherent strategies across all levels of governance. The full involvement of all segments of society, including local communities, will also be needed as we transition toward a new era of sustainable development.

Some of the linked variables at the junction of biodiversity and human health described throughout this volume are schematically represented in Figure 1.

This volume comprises three main parts.

Part One defines the concepts of biodiversity and health, introduces concepts such as the social and environmental determinants of health, biodiversity and ecosystem services, and provides a broad overview of the different ways in which biodiversity and health are linked. It also considers common drivers of change that impact on both global public health and biodiversity, and calls for the use of integrative, interdisciplinary framework approaches that attempt to unite different fields such as "One Health", "Ecohealth" and the ecosystem approach.

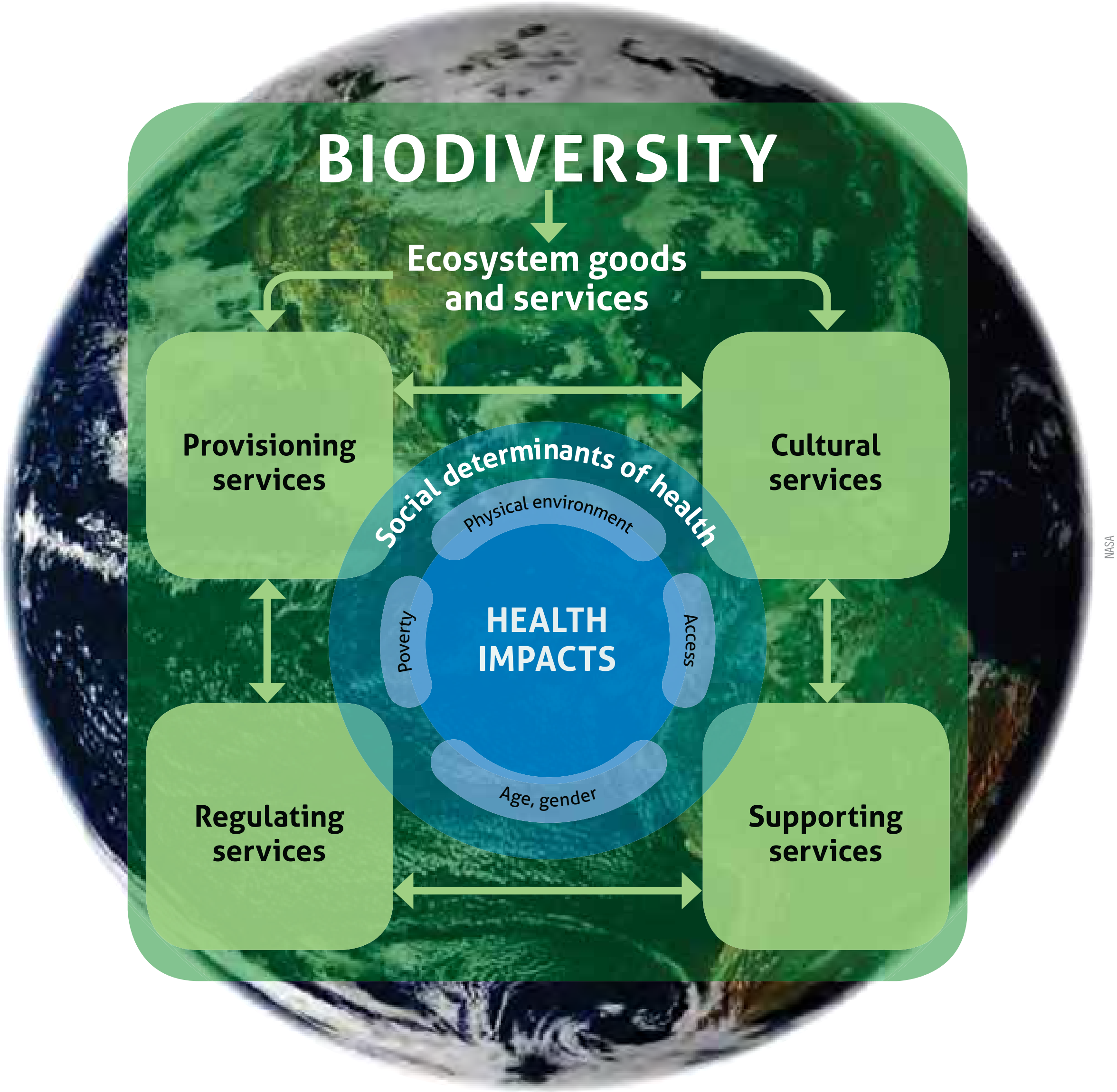
Part Two examines how biodiversity is related to specific thematic areas at the biodiversity–health nexus, specifically addressing: water and air quality; agricultural biodiversity and food security; nutrition and health; infectious diseases; microbial communities and NCDs; the contribution of biodiversity to health care and the impact of pharmaceuticals on biodiversity; traditional medicine; physical and mental health and well-being, and cultural ecosystem services.

Finally, Part Three discusses some critical cross-cutting themes at the intersection of biodiversity and health, including climate change, disaster risk reduction, and sustainable consumption and production. It also suggests broad strategies and approaches to integrate a consideration of the linkages between biodiversity and human health into public policy, and identifies preliminary tools and research gaps for further exploration. The volume concludes by highlighting how better consideration of the linkages between biodiversity and human health will contribute to the post-2015 Development Agenda.

This State of Knowledge Review builds upon and extends the health synthesis of the Millennium Ecosystem Assessment (WHO 2005) and other recent studies (Chivian & Bernstein 2008; Sala et al. 2012). As further discussed in Chapter 2, the review casts a wide net, considering the direct and indirect linkages between human health and biodiversity (including its components and ecosystems).

Biodiversity plays a critical role in ecosystem functioning and also yields direct and indirect benefits (or ecosystem services) that support human and societal needs, including good health, food and nutrition security, energy provision, freshwater and medicines, livelihoods and spiritual fulfilment. These, in turn are mediated by the social determinants of health (such as age, gender and access to health care). Multidisciplinary approaches can help us to better analyse and evaluate the interactions between these different variables to better develop more coordinated, coherent and integrated policies.

FIGURE 1: Linkages and co-dependencies at the intersection of biodiversity and human health



LUIS ASCUI FOR ASIAN DEVELOPMENT BANK / FLICKR

2. Biodiversity and human health linkages: concepts, determinants, drivers of change and approaches to integration

1. BIODIVERSITY, HEALTH AND INTERACTIONS

1.1 What is biodiversity?

Biological diversity, most commonly used in its contracted form, biodiversity,[1] is the term used to describe the variety of life on earth, including animals, plants and microbial species. It has been estimated that there are some 8.7 million eukaryotic species on earth,[2] of which some 25% (2.2. million) are marine, and most of them have yet to be discovered (Mora et al. 2011). Biodiversity not only refers to the multitude of species on earth, it also consists of the specific genetic variations and traits within species (such as different crop varieties),[3] and the assemblage of these species within ecosystems that characterize agricultural and other landscapes such as forests, wetlands, grasslands, deserts, lakes and rivers. Each ecosystem comprises living beings that interact with one another and with the air, water and soil around them. These multiple interconnections within and between ecosystems form the web of life, of which humans are an integral part and upon which they depend for their very survival. It is the combination of these life forms and their interactions with one another, and with the surrounding environment, that makes human life on earth possible (CBD 2006).

The Convention on Biological Diversity (CBD) defines biodiversity as: "the variability among living organisms from all sources including, inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species, and of ecosystems".[4] Biodiversity encompasses much more than the variety of life on earth; it also includes biotic community structure, the habitats in which communities live, and the variability within and among them.

Thus, biodiversity extends beyond the simple measurement of species numbers to include the complex network of interactions and biological structures that sustain ecosystems (McCann 2007; Maclaurin and Sterelny 2008). Although

[1] It has been argued that the rapidly popularized term biodiversity was coined by Walter G. Rozen in 1986 (e.g. Maclaurin and Sterelny 2008; Sarkar and Margules 2002).

[2] Eukaryotic cell species (including humans) are those that have a nucleus and internal compartments. Conversely, most prokaryotic cell species are made up of a single cell.

[3] For example, two species of rice contain over 120 000 genetically different varieties (CBD 2006).

[4] Convention on Biological Diversity, Article 2.

"species richness" is one of biodiversity's key components, the two terms are not synonymous. The widely accepted definition of biodiversity adopted by the CBD is flexible, inclusive, and reflective of the levels and complexities of biotic and abiotic interactions. It recognizes levels of variability within species, between species, and within and between ecosystems as integral to the ecological processes of which they are a part (Mace et al. 2012). It is also understood that variability manifests itself differently at various temporal and spatial scales (Nelson et al. 2009; Thompson et al. 2009).

The scope of the Convention is broader still; its objectives – "the conservation of biological diversity, the sustainable use of its components and the fair and equitable sharing of the benefits arising out of the utilization of genetic resources" – indicate an interest in the components of biodiversity (including individual species) and genetic resources.

1.2 What is health?

The constitution of the World Health Organization (WHO) defines health as "a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity". Health is a dynamic concept that is influenced by a range of interacting social, biological, physical, economic and environmental factors. As such, health is one of the most important indicators of sustainable development. While social status and economic security are perhaps most important in determining an individual's capacity to manage her or his health and to maintain a healthy lifestyle, the role of environmental and ecosystem change in determining health status are increasingly recognized within the health, environment and development communities. The 2005 reports of the Millennium Ecosystem Assessment have helped to increase understanding of the relationships between the environment and human well-being. Together, these reports have marked a turning point in highlighting the importance of ecosystems and the goods and services that they provide to public health and to economic development alike (MA 2005a, b).

The findings of the Millennium Ecosystem Assessment and of large-scale national and regional assessments have made it clear that it is increasingly important for people in the public health sector to recognize that human health and well-being are influenced by the health and integrity of local ecosystems, and frequently by the health of local plant and animal communities. The interactions between people and biodiversity can determine the baseline health status of a community, providing the basis for good health and secure livelihoods, or creating the conditions responsible for morbidity or mortality.[5] In many cases, the long-term success and sustainability of public health interventions is determined by the degree to which ecological factors are taken into account. In the same way that economic factors must often be addressed, biodiversity and its importance to the functioning of ecosystems must also be considered. As noted in the earlier definition of biodiversity, this concept must also be explored at multiple geographical and temporal scales for the health sector. Public health policies must also ensure that the relevance of biodiversity is assessed and accounted for within various plans or projects. Similarly, biodiversity conservation initiatives must also account for how such projects may affect public health, whether the resulting impacts are positive or negative. As the global community works towards the implementation of the United Nations Sustainable Development Goals, the importance of biodiversity to livelihoods, poverty eradication and human well-being is also of paramount importance.

1.3 Biodiversity–health interactions

Biodiversity and human health are linked in many ways, and a broad scope is taken in this State of Knowledge Review. Further to Mace and colleagues (2012), we look at "biodiversity" in a broad sense, including not only species richness and the genetic diversity within species ("biodiversity, narrow sense") but also

[5] Morbidity refers to the incidence of a disease across a population, while mortality refers to the rate of death in a population.

the components of biodiversity (species and genotypes), and habitats and ecosystems. Thus, the distribution and abundance of species, and the extent of natural habitats, are relevant, *in addition to* diversity per se. Moreover, we consider not only the direct effects of biodiversity or its components on human health, but also the (indirect) effects that are due to biodiversity's role in supporting ecosystem processes and functioning (see section 3). Further, we examine drivers of change that are common to both biodiversity loss (or change) and health status. Finally, we are also concerned with the impacts of the interventions made in the health sector on biodiversity and vice versa. Thus, this State of Knowledge Review casts a broader net than other recent reviews (e.g. Hough 2014).

Like Sandifer et al. (2015), we consider a broad range of pathways through which biodiversity may provide health and well-being benefit to people: psychological (e.g. green spaces and iconic wildlife; see Chapter 12), physiological (directly through the human microbiome, and indirectly through exercise in green spaces, see Chapters 8 and 12), regulation of the transmission and prevalence of some infectious diseases (see Chapter 7), provision of food and good nutrition (Chapters 5 and 6), clean air and water (Chapters 3 and 4), the provision of traditional and modern medicines (Chapters 9 and 11) and the impact of some pharmaceuticals on the environment (Chapter 11).

Box 1 and Figure 1 provide a typology of biodiversity–health interactions.

The interactions between biodiversity and health are manifested at multiple scales from individuals, through communities and landscapes to a planetary scale (Figure 1). At the scale of the **individual** person, the human microbiota – the commensal microbial communities present in our gut, in our respiratory, oropharyngeal and urogenital tracts and on our skin – contribute to our nutrition, help regulate our immune system, and prevent infection. Interactions among family members and the wider environment may be important in the maintenance and turnover of this diversity. At the **community** level (such as **farms**), many aspects of biodiversity – among crops and livestock, associated pollinators and pest control organisms and in soils – support agricultural production. Ecosystem services in the wider **landscape** of biodiversity underpin a host of ecosystem services, including water provision and erosion control. The functioning and integrity of the biosphere at a planetary scale (i.e. **global** level) is also understood to depend on biodiversity.

2. EQUITY AND SOCIAL DIMENSIONS OF HEALTH AND BIODIVERSITY

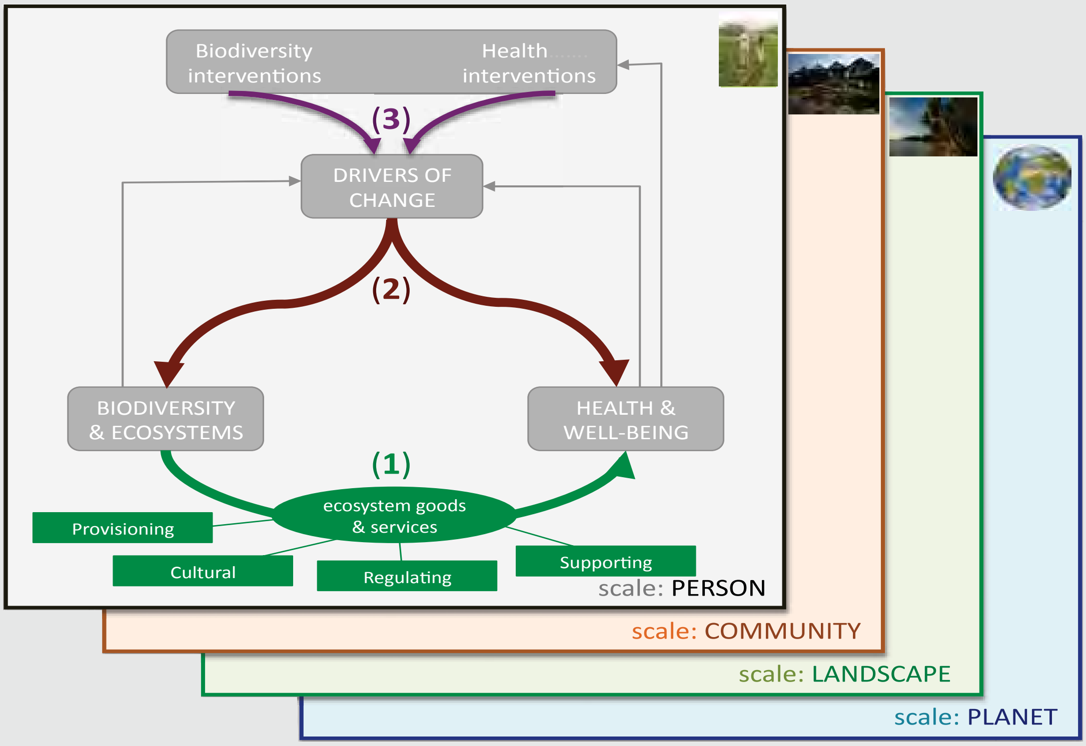
Human population health is determined, to a large extent, by the social, economic and environmental determinants of health (United Nations Task Team on Social Dimensions of Climate Change 2011; WHO 2008). The social, economic and behavioural aspects of the human condition interact with the environment, including critical elements of biodiversity, biodiversity losses and gains, and ecosystem services.

Biodiversity and its changes (losses and gains) are, to a great extent, the result of anthropogenic influences (Mora and Zapata 2013). The social dimensions of biodiversity are present both in relation to these drivers of change and in relation to how the impacts of biodiversity change are mediated among groups of differing socioeconomic status. Biodiversity loss is impacted by anthropogenic drivers, such as overexploitation of natural resources, human-induced climate change and habitat loss. Large-scale social and economic processes and systems affect biodiversity, and the social, economic and environmental dimensions of ecological sustainability at risk (UNESCO 2013).

Environmental determinants of health (such as air quality, food security, water security, freedom from disease, etc.) are interrelated and adversely affected by the reduced ability of degraded ecosystems and biota to adapt to the impacts of climate change, air pollution, natural disasters or water scarcity. Many of the dynamics between biodiversity and human health are in the area of infectious, vector-borne diseases. In some cases, biodiversity loss (such as that associated with deforestation) may enhance the risk of some diseases such as malaria (Chaves

Box 1. A typology of biodiversity–health interactions

FIGURE 1:



PHOTOS: ASIAN DEVELOPMENT BANK / FLICKR

(1) A first type of interaction is where biodiversity gives rise to health benefits. (Biodiversity → Health). For example, different species (as well as crop varieties and livestock breeds) provide nutrients and medicines. Biodiversity also underpins ecosystem functioning, which provides services such as water and air purification, pest and disease control, and pollination. Biodiversity can also be a source of pathogens and thus have negative impacts on health. Changes in biodiversity would lead to changes in the health benefits. Drivers of such changes extend the causal change upstream (Driver of change → loss of biodiversity → reduction in health benefits).

(2) A second type of interaction arises from drivers of change that affect both biodiversity and health in parallel. (Driver of change → impacts on health <u>and</u> on biodiversity). For example, air and water pollution can lead to biodiversity loss and have direct impacts on health. Deforestation (or other land-use change or ecosystem disturbance) can lead to loss of species and habitats, and also increased disease risk for humans. Conversely, moderated meat consumption can reduce the pressures on biodiversity (less land-use change; lower greenhouse gas emissions) and also have health benefits for individuals. In addition to the parallel effects of the driver on biodiversity and health, there may be additional impacts of the change in biodiversity on health. For example, water pollution, in addition to harming health though loss of drinking water quality, could lead to collapse of aquatic ecosystems through eutrophication leading to fish mortality and consequent negative effects on nutrition.

(3) A third type of interaction arises from the impacts of health sector interventions on biodiversity (Health intervention → biodiversity) and of biodiversity-related interventions on health (Biodiversity intervention → health). For example, use of pharmaceuticals may lead to the release of active ingredients in the environment and damage species and ecosystems. Again, these may have negative knock-on effects on human health. On the other hand, protected areas or hunting bans could deny access of local communities to bushmeat and other wild foods, with negative nutritional impacts. Positive interactions of this type are also possible. For example, establishment of protected areas may protect water supplies, with positive health benefits.

et al. 2011; Hahn et al. 2014; Laporta et al. 2013), while in others, biodiversity gains (such as that associated with reforestation) may also sometimes increase the risk for other diseases (Levy 2013; Ostfeld and Keesing 2000).

In addition to environmental determinants, social and economic determinants also influence the dynamics between biodiversity changes and human health. The inequities of how society is organized mean that the freedom to lead a flourishing life and to enjoy good health is unequally distributed between and within societies. This inequity is seen in the conditions of early childhood and schooling, the nature of employment and working conditions, the physical form of the built environment, and the quality of the natural environment in which people reside. Depending on the nature of these environments, different groups will have different experiences of material conditions, psychosocial support and behavioural options, which make them more or less vulnerable to poor health. Social stratification likewise determines differential access to and utilization of health care, with consequences for the inequitable promotion of health and well-being, disease prevention, and recovery from illness and survival. This unequal distribution of health-damaging experiences is not in any sense a "natural" phenomenon but is the result of a toxic combination of poor social policies and programmes, unfair economic arrangements and power relationships. (Commission on Social Determinants of Health 2008).

Population groups more reliant on biodiversity and ecosystem services, especially on provisioning services such as timber, water and food, are usually more vulnerable to biodiversity loss and those less covered by social protection mechanisms (e.g. health insurance). Vulnerable groups include indigenous populations, specific groups dependent on biodiversity and ecosystem services and, for example, subsistence farmers. Detrimental changes to biodiversity and the resulting risks and burden of human health problems are inequitably distributed in specific social–ecological settings. These inequalities affect both individual and community health either directly (whether it be in isolation or through an interaction with other determinants) or indirectly (e.g. access to healthy food).

Detrimental changes to biodiversity and the resulting risks and burden of human health problems are inequitably distributed in specific social–ecological settings. Populations exposed to the greenest environments have been found to also have the lowest levels of health inequality related to income deprivation, suggesting that healthy physical environments can be important for reducing socioeconomic health inequalities (Mitchell and Popham 2008). Equity issues are not only important in relation to different groups within a country, but also in relation to different vulnerabilities among countries. Developing countries are more reliant on biodiversity and ecosystem services than developed ones, and their health systems are usually less prepared to protect the health of their populations, which leads to greater negative health impacts of biodiversity change. Between countries, biodiversity loss is related to income inequality (Mikkelson et al. 2007). For example, over 1 billion people, mainly in developing countries, rely on fisheries as their primary source of animal protein (Gutiérrez et al. 2011).

Different gender roles in relation to biodiversity management, conservation and use can also have an impact on human health, and more attention needs to be paid to these gender dimensions (WHO 2011, 2008). Access to, use and management of biodiversity have different health impacts on women and men and boys and girls, determined by gender norms, roles and relations (Gutierrez-Montes et al. 2012). Social norms and values determine different gender roles and relations, which in turn, are translated into different responsibilities, obligations, benefits and rights in relation to biodiversity (Manfre and Ruben 2012). In addition to the lack of political will, and frequently weak institutional capacity and legal frameworks that fail to assess and address different gender roles, there is a lack of sex-disaggregated data on biodiversity access, use and control, which makes it very difficult to conduct a gender analysis and therefore design adequate responses targeting specifically those most vulnerable population groups (Castaneda et al. 2012).

However, it is widely accepted that many of the adverse impacts of biodiversity loss are impacting already vulnerable groups of people, specifically populations who are dependent on biodiversity and ecosystem services (forest dwellers, indigenous populations, women and girls, etc.). Biodiversity losses in specific social–ecological settings and the resulting health effects on marginalized populations are often triggered by large-scale processes beyond the control of the populations at risk. Climate change or large-scale mining or logging projects may have negative impacts on biodiversity, and increase social and economic inequalities. For example, it is estimated that 1 billion people only produce 3% of global greenhouse gas emissions. A social justice perspective is, therefore, needed to address the various equity dimensions in the biodiversity and health dynamic (Walter 2003).

The social sciences are important contributors to research and policy-making in biodiversity and health. In addition to gender analysis, a multifaceted approach is needed to effectively tackle the equity and social dimensions of health and biodiversity. Social research illuminates social vulnerabilities, and has the potential to engage and mobilize people most affected by biodiversity loss, e.g. indigenous populations. The social sciences also play an important role in determining policy options for health, biodiversity and ecosystem management (Artner and Siebert 2006; Duraiappah and Rogers 2011; Gilbert et al. 2006). Inter-, multi- and transdisciplinary research can provide valuable insights into the drivers of disease emergence and spread, contribute to identifying previous patterns of disease risk, and help to predict future risks through the lens of social–ecological systems (Folke 2006; Gilbert et al. 2006; UNESCO 2013). For example, interdisciplinary work on the social determinants of health can also provide valuable insights into the drivers of disease emergence and spread, contribute to identifying previous patterns of disease risk and help to predict future risks.

Relevant tools that could be used to understand the equity and social dimensions of health and biodiversity for any relevant policy or programme include social impact assessments, health impact assessments and strategic impact assessments. Whatever tool is used, it is key to ensure that all health, environmental, and social considerations and impacts are *integrated* within the assessment. As discussed in section 5 of this chapter and Part III of this volume, solutions to biodiversity and health challenges also necessitate the sustained engagement of multiple stakeholders, both in governments, civil society, and in nongovernmental and international organizations. The social sciences are, therefore, important contributors to research and policy-making in biodiversity and health (UNESCO 2013), and to the large-scale social and behavioural changes required to achieve the objectives of sustainable development.

3. BIODIVERSITY, ECOSYSTEM FUNCTIONS AND SERVICES

Scientific knowledge of the impacts of biodiversity loss on ecosystem functioning has increased considerably in the past two decades (Balvanera et al. 2014; Cardinale et al. 2012; Reis et. al. 2012; Naeem and Wright 2003; Loreau et al. 2001; Tilman et al. 1997), as well as corresponding knowledge of its implications for public health (Myers et al. 2013). In this section, we summarize key elements of the relationship between biodiversity, ecosystems and ecosystem functioning, its connection to ecosystem services, and the components that influence the quantity, quality and reliability of ecosystem services, and that contribute to ecosystem resilience.

There is strong evidence of the relationship between biodiversity and ecosystem functioning and, in some cases, we can directly link this to the ecosystem services necessary to sustain human health (Loreau et al. 2001; Balvanera et al. 2006; Cardinale et al. 2012; Balvanera et al. 2014). In other cases, we do not yet have complete evidence of this relationship (Schwartz et al. 2000; Cardinale et al. 2012). While there is broad consensus within the scientific community on several aspects of the relationship between biodiversity, ecosystem functioning and the consequences of its loss on the ability of ecosystems to provide services, the full range of impacts of biodiversity loss on ecosystem functioning is not fully understood (Reiss et al. 2009; Hooper et al. 2005).

3.1 Biodiversity, ecosystem processes and properties

Ecosystems comprise physical and chemical biotic (e.g. plants, animals, humans) and abiotic (e.g. light, oxygen, temperature, soil texture and chemistry, nutrients) interactions (Currie 2011). Ecosystem processes include decomposition, nutrient cycling (e.g. water, nitrogen, carbon and phosphorus cycling), production (of plant matter), as well as energy and nutrient fluxes. A healthy ecosystem – one that performs its various functions well and where equilibrium is maintained – is dependent upon biodiversity. This is often referred to as ecosystem integrity, ecosystem stability or ecosystem health.

Fluxes of energy, biogeochemical cycles such as nutrient cycling and oxygen production, and community dynamics such as predator–prey interactions are regulated by the earth's biota. The *attributes* (including composition and abundance) and interactions of biotic and abiotic components determine ecosystem *processes* and their *properties*, and they influence changes in each of the latter over space and time (Reiss et al. 2009). The provision of essential goods and services, including those essential to sustaining human life, is reliant on the properties, processes and maintenance of ecosystems (Naeem and Wright 2003; Balvanera et al. 2006; Reiss et al. 2009, 2010). The quality, quantity and security of the essential services that we derive from ecosystems are determined by several dynamic and interlinked factors, including different components of biodiversity, underlying physical and biological processes (each with their own characteristics and thresholds), and complex responses to environmental stressors such as pollution and climate change (Mace 2012; Balvanera et al. 2006).

The specific components of biodiversity (e.g. genes, species) and attributes (e.g. variability, composition) that underpin the ecosystem services that, in turn, support human health and well-being may differ among the services or goods in question, and on the processes upon which they rely. The diverse functional traits of species within a community can also influence ecosystem properties, and their examination can contribute to understanding variations in ecosystem functions (Hooper et al. 2005; Tilman et al. 1997; Haines-Young and Potschin 2010; Naeem and Wright 2003) and resilience (Mori et al. 2013; Elmqvist 2003). In this sense, species' functional characteristics can be critical to ecosystem services; their loss can result in permanent changes.

Twenty years of work on the relationship between biodiversity and ecosystem functioning has generated a number of controversies and spurred efforts to develop scientific consensus. Cardinale et al. (2012) conclude that diverse communities tend to be more productive both because they contain key species that have a large influence on productivity, and because differences in functional traits among organisms increase the total capture of resources (light, water). Thus, biodiversity loss reduces the efficiency by which ecological communities capture biologically essential resources, produce biomass, and decompose and recycle biologically essential nutrients. They report that the impact of biodiversity on any single ecosystem process is non-linear and saturating, such that change accelerates as biodiversity loss increases. They also point to mounting evidence that biodiversity increases the stability of ecosystem functions through time.

3.2 Ecosystem services

Human health ultimately depends upon ecosystem products and services (e.g. availability of fresh water, food and fuel sources), which are required for good health and productive livelihoods. Many ecosystems, such as marine areas, forests, grasslands and wetlands, contribute to regulation of the world's climate, and can also influence local microclimates. People depend directly on

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ecosystems in their daily lives, including for the production of food, medicines, timber, fuel and fibre, but also in ways that are not always apparent or appreciated. Our natural capital is not only the source of our food, but also provides less tangible benefits, such as spiritual enrichment, and areas for recreation and leisure. Ecosystems also play important roles in the water cycle, regulating the flow of water through the landscape, and the amount of sediments and contaminants that affect important water resources. These and other important benefits, called "ecosystem goods and services", are essential to our society, our economic development, and our health and well-being. Biodiversity loss can have direct, and sometimes significant, human health impacts, particularly if ecosystem services are no longer adequate to meet social needs. Indirectly, changes in ecosystem services affect livelihoods, income, local migration and, on occasion, may even cause political conflict.

The first comprehensive scientific appraisal of the condition and trends of ecosystem services for health and well-being, the Millennium Ecosystem Assessments,[6] adopted four major categories of ecosystem services: provisioning services such as water, food and timber; regulating services such as pest control, climate regulation and regulation of water quality; cultural services including recreational and spiritual benefits; and supporting services such as photosynthesis, soil formation and nutrient cycling. Each category is vital for human and community health, as well as ecosystem resilience. The study concluded that ecosystems processes have changed more rapidly

[6] While the Millennium Assessment has been instrumental in evaluating the conditions and trends of ecosystems for health, the notion of ecosystem services can be traced as far back as the 1970s (Haines-Young and Potschin 2010). The impetus for placing human needs at the centre of biodiversity management is also covered by the 12 principles of the ecosystem approach adopted by the Convention on Biological Diversity (COP 5 decision the V/6).

since the mid-twentieth century than at any other time in recorded human history. Among the 24 categories of ecosystem services assessed, 15 of them were in a state of decline, the majority of them regulating and supporting services (MA 2005). Declining services include pollination, the ability of agricultural systems to provide pest control, the provision of freshwater, marine fishery production, and the capacity of the atmosphere to cleanse itself of pollutants. Most ecosystem services that were found to be increasing were provisioning services, including crops, livestock and aquaculture. Consumption was also increasing of all services across all four categories. These increases have helped to generate and sustain the increases in human health and well-being seen over the same period. However, the decline of many other ecosystem services – mostly the regulating and supporting services – threatens to undermine this progress, presenting threats to human health and well-being (Chivian and Bernstein 2008; Haines-Young and Potschin 2010; McMichael and Beaglehole 2000), several of which are described throughout this technical volume.

In general, aggregate terms, socioeconomic progress has benefited human health and well-being, but at a cost to the underlying natural resource base. Raudsepp-Hearne et al. (2010) examined several hypotheses to explain this apparent paradox and call for efforts to expand our understanding of the complex cross-scale interactions between ecosystem services, human activities and human well-being.

3.3 Biodiversity loss, biosphere integrity and tipping points

Ecosystem management strategies aimed at maximizing conservation and public health co-benefits must consider that systems have emergent properties that are not possessed by their individual components: they are more than the sum of their parts. One example is the resilience of ecosystems to absorb shock in the face of disturbance (such as pests and disease, climate change, invasive species, or the harvesting of crops, animals or timber) and return to their original structure and functioning. Ecosystems can be transformed if a change in ecosystem structure crosses a given threshold. Structural changes may be manifested as a result of the removal of key predators or other species from the food web (Thomson et al. 2012), the simplification of vegetation or soil structure, increased or decreased aridity, species loss and many other factors. Biodiversity loss is continuing, and in many cases increasing (Butchart et al. 2010; Tittensor et al. 2014). Biodiversity loss has been identified as one of the most critical drivers of ecosystem change (Hooper et al. 2012). Changes in the diversity of species that alter ecosystem function may directly reduce access to ecosystem services such as food, water and fuel, and also alter the abundance of species that control critical ecosystem processes essential to the provision of those services (Chapin et al. 2000).

Ecosystem regime shifts, including "tipping points", have been widely described and characterized at local levels (for example, eutrophication of freshwater or coastal areas due to excess nutrients; collapse of fisheries due to overfishing; shifts of coral reefs to algae-dominated systems; see Sheffer 2009; CBD 2010). There is growing concern that regime shifts could occur at very large spatial scales over the next several decades, as human–environment systems exceed limits because of powerful and widespread driving forces that often act in combination: climate change, overexploitation of natural resources, pollution, habitat destruction, and the introduction of invasive species (Leadley et al. 2014; Barnosky et al. 2012; Hughes et al. 2013). Cardinale et al. (2012) suggest that the impacts of biodiversity loss on ecological processes might be sufficiently large to rival the impacts of climate change and many other global drivers of environmental change.

Leadley et al. describe scenarios for regional-scale shifts that would have large-scale and profound implications for human well-being (Leadley et al. 2014). The unprecedented pressures of human activity on biodiversity and on the earth's ecosystems may also lead to potentially irreversible consequences at a planetary scale, and this prospect has led to the identification of processes and associated thresholds, and to the development of various approaches[7] to define preconditions for human development on a planetary scale (Rockström et al. 2009; Barnosky et al. 2012, Steffen et al. 2015; see also Mace et al. 2014). Global efforts to pursue sustainable development will continue to be compromised if these critical pressures are not countered in a more rigorous, systematic and integrated fashion.

4. DRIVERS OF CHANGE

In recent decades, the impact of human activity on the natural environment and its ecosystems has been so profound that it has given rise to the term *anthropocene*, popularized by Nobel prize-winning chemist Paul Crutzen, delimiting a shift into a new geological epoch, in which human activity has become the dominant force for environmental change (Crutzen 2002). Anthropogenic pressures, demographic change, and resulting changes in production and consumption patterns are also among the factors that contribute to biodiversity loss, ill-health and disease emergence. These pressures have shown a "great acceleration", especially in the past 50 years (Steffen et al. 2015b). While some human-induced changes have garnered public health benefits, such as the provision of energy and increased food supply, in many other cases they have been detrimental to the environment, ecosystems and corresponding services, as well as human health (Myers et al. 2013; Cardinale et al. 2012; Balmford and Bond 2005; McMichael and Beaglehole 2000). In many cases, the ecological implications are immense and the need to address them pressing if our planet is to provide clean water, food, energy, timber, medicines, shelter and other benefits to an ever-increasing population. The rise in demographic pressures and consumption levels will translate into unprecedented demands on the planet's productive capacity, and concomitant pressures on the earth's biological resources may undermine the ability of ecosystems to provide life-sustaining services (CBD 2010; McMichael and Beaglehole 2000).

Social change and development biases (such as urbanization, poverty and inequity) further influence the drivers of biodiversity loss and ill-health. Macroeconomic policies and structures, and public policies that provide perverse incentives or fail to incorporate the value of biodiversity frequently compound the dual threat to biodiversity and public health. Both the impacts of biodiversity loss and ill-health are likely to be most pronounced among the world's poorest, most vulnerable populations,[8] which are often those most immediately reliant on natural resources for food, shelter, medicines, spiritual and cultural fulfilment, and livelihoods (MA 2005). As indicated above, these vulnerable groups are also generally those least able to access substitutes when ecosystem services are degraded. In addition to the immediate usefulness of natural resources, the intrinsic value of nature to so many, its cultural and spiritual contributions, and the right of future generations to inherit a planet thriving with life also should not be overlooked.

The drivers (causes) of ill-health and human, animal and plant disease often overlap with the drivers of biodiversity loss. Some of the principal common drivers, identified in the third edition of Global Biodiversity Outlook (GBO 3) and reiterated in its fourth edition, include: habitat change, overexploitation and destructive harvest, pollution, invasive alien species and climate change (CBD 2010, 2014), all of which may be exacerbated by environmental changes.

[7] Rockström and colleagues (2009), updated by Steffen et al. (2015), describe nine "planetary boundaries" that have been identified: including biosphere integrity (terrestrial and marine); climate change; interference with the nitrogen and phosphorus cycles; stratospheric ozone depletion; ocean acidification; global freshwater use; changes in land use; chemical pollution; and atmospheric aerosol loading. The metrics used to define the biodiversity/biosphere integrity planetary boundaries has been challenged, including biodiversity loss, for its measurement of biodiversity as "global species extinction rate" and "the abundance, diversity, distribution, functional composition and interactions of species in ecosystems" were not considered in its 2009 (Mace et al. 2014: 296).

[8] For example, Butchart et al. (2010) indicate that more than 100 million of the world's poor people, especially reliant on biodiversity and the services it provides, live in remote areas within threatened ecoregions.

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As the majority of human infectious agents have originated in animals (known as “zoonotic diseases”), including the infection leading to HIV/AIDS (from chimpanzees hunted for human consumption), animal and environmental links to human infectious diseases are highly relevant (Taylor et al. 2001). While the ties between infectious diseases and biodiversity are perhaps the most frequently cited, biodiversity loss also has significant and myriad implications for noncommunicable diseases (NCDs) and the socioeconomic determinants of health. Examples of these are highlighted for each of the major drivers of biodiversity loss identified above.

The pressing need to jointly address both social and environmental determinants of health (Bircher and Kuruvilla 2014) has been widely acknowledged through various multilateral agreements. However, the role of biodiversity as a mediating influence on human health (through the loss of ecosystem services, which are themselves mediated by ecological processes), while gaining more widespread attention since Rio, merits much more systematic assessment as well as more structured, coherent, and cross-cutting policies and strategies. These critical linkages should be translated into concrete policy targets as we embark on a new series of global commitments on sustainable development as the MDGs reach their term in 2015.

4.1 Habitat change

Land-use change (e.g. full or partial clearing for agricultural production or natural resource extraction, such as for as timber, mining and oil) is the leading driver of biodiversity loss in terrestrial ecosystems. Alteration of native habitats may also reduce resilience; for example, deforested areas may experience soil erosion, increasing ecological risks of extreme weather events such as sudden flooding, and limited food production potential from reduced soil enrichment. Furthermore, habitat changes such as deforestation directly alter the capacity of carbon sinks and thus further increase the risks of climate change.

Land-use change is also the leading driver of disease emergence in humans from wildlife (Jones et al. 2008). Changes to habitats, including through altered species composition (influenced by conditions that may more favourably support carriers of disease, as seen with malaria-harbouring vectors in cleared areas of the Amazon) and/or abundance in an ecosystem (and thus potential pathogen dispersion and prevalence), and the establishment of new opportunities for disease transmission in a given habitat, have major implications for health. Human-mediated changes to landscapes are accompanied by human encroachment into formerly pristine habitats, often also accompanied by the introduction of domestic animal species, enabling new types of interactions among species and thus novel pathogen transmission opportunities.

4.2 Overexploitation and destructive harvest

Overexploitation of biodiversity and destructive harvesting practices reduce the abundance of the populations of species concerned, and in some cases, can threaten the survival of the species itself. Demand for wild-sourced food is increasing in some areas. The wildlife trade, for purposes such as supplying the pet trade, medicinal use, horticulture and luxury goods, is increasing globally, exacerbating pressures on wild populations. Practices for harvest, including unregulated administration of chemicals for the capture of animals (e.g. the release of cyanide or trawling practices for fishing) may also have impacts on non-target species, and/or unsustainable harvests may alter ecological dynamics, such as diminished potential for seed dispersion and implications for food chains (affecting also the humans who depend on them). As native biodiversity declines, local protein sources from subsistence hunting or gathering may be diminished, causing inadequate nutrition if alternatives are unavailable or lack necessary nutrients. Additionally, bushmeat hunting and consumption, sometimes in areas that have not been previously targeted for food sourcing (for example, in newly established mining camps in formerly pristine habitat) may pose direct novel infectious disease transmission risks. Intensification of harvest and exploitative practices, such as the mixing of wildlife and domestic species in markets, as well as the mixing and spread of their pathogens, can create global epidemics, as seen with the 2003 outbreak of severe acute respiratory syndrome (SARS).

4.3 Pollution

Environmental pollution poses direct threats to both biodiversity and human health in many ways. Pollutant exposure risk is potentially increased for top-of-the-chain consumers such as humans and marine mammals through bioaccumulation along the food chain, as seen with mercury. Air pollution exposure presents risks of respiratory diseases. Other so-called “lifestyle diseases” (such as obesity and diabetes) may be influenced by access to physical fitness, which may be limited by outdoor and indoor air pollution levels. Chemicals, such as pharmaceuticals or plastics containing endocrine-disrupting substances, may be dispersed on entering water sources and other environmental settings, posing acute, chronic or recurring exposures in humans and animals. Wide-scale application of antimicrobials for human and animal medicine and food production, much of which is excreted into the environment, is resulting in rapid changes to microbial composition, as well as driving development of antimicrobial-resistant infections. Contaminated water may enable persistence of human infectious agents and their diseases, such as cholera-causing *Vibrio* and parasitic worm-transmitted schistosomiasis.

4.4 Invasive alien species

Invasive alien species (IAS) pose direct threats to native and/or endemic species. The introduction of IAS may result in invasive species out-competing important food and traditional medicine sources for human populations, as well as causing fundamental impacts on ecosystems that may influence health processes. Examples of this include impaired water quality from the introduction of zebra mussel in the United Kingdom and North America, altered soil quality through the spread of weeds, and the reduced species decomposition facilitated by feral pigs grazing on native plants as well as agricultural land. In addition to these detrimental impacts, IAS pose risks of disease introduction and spread for native wildlife, agricultural species and humans. As global trade and travel continues to increase, so do the health risks; changing climactic conditions may also enable establishment of IAS where climate would have previously limited survival, demonstrated with alarming clarity in the case of the pine mountain beetle invasion in western Canada.

4.5 Climate change

The direct and indirect impacts of climate change also pose risks for biodiversity and health; for example, shifts in species ranges may also facilitate changes in pathogen distribution and/or survival, as projected for Nipah virus (Daszak et al. 2013). Climate change also contributes to ocean acidification, coral bleaching and diseases in marine life, as reef-building coral species are threatened with extinction. These in turn have significant implications for the large biological communities that coral reefs support and that sustain human health (Campbell et al. 2009). More extreme weather patterns and rising sea levels (e.g. drought, flooding, early frost) may also be detrimental to food and water security, especially for populations dependent on subsistence farming and natural water sources. Human populations may also suffer acute health impacts from extreme weather (e.g. heat or cold exposure injuries).

4.6 Demographic factors, including migration

In addition to the direct drivers of biodiversity loss, large-scale societal and demographic changes, or intensified reliance on ecosystems for subsistence or livelihoods, often linked to biodiversity changes, may also impact vulnerability to disease. For example, new human inhabitants (recent immigrants) might not have immunity to zoonotic diseases endemic to the area, making them particularly susceptible to infection. Women who are required to butcher harvested wildlife, or men who hunt the game, may be particularly at risk. Moreover, those sectors of society that lack adequate income to purchase market alternatives may be more likely to access forest resources (including wildlife) for food and trade. Thus, there are likely socioeconomic and gender-specific relationships to these types of disease risks and exposures (WHO 2008). Disease may also worsen the economic status of a population; vector-borne and parasitic diseases, the burden of which is driven by ecological conditions, have been shown to worsen the poverty cycle (Bonds et al. 2012).

4.7 Urbanization as a challenge and an opportunity to manage ecosystem services

Urbanization, the demographic transition from rural to urban, is associated with shifts from an agriculture-based economy to mass industry, technology and service.[9] With the majority of the world's population now living in urban areas and this proportion expected to increase, it is expected that urban health should become a major focus at the intersection of global public health and conservation policy.[10] Urbanization is also closely linked with the social determinants of health, including development, poverty and well-being.

While urbanization is often associated with increasing prosperity and good health, urban populations also demonstrate some of the world's most prominent health disparities, in both low- and high-income countries. Rapid migration from rural areas as well as natural population growth are putting further pressure on limited resources in cities, and in particular, in low-income countries.[11]

[9] For the first time in history, the majority of the world's population lives in cities, and this proportion continues to grow. One hundred years ago, 20% of the people lived in urban areas. By 2010, this proportion increased to more than half. By 2030, it is expected that the number of people in urban areas will increase to 60%, and in 2050, to 70%. For example, see World Health Organization Global Health Observatory (GHO) data: urban population growth. (www.who.int/gho/urban_health/situation_trends/urban_population_growth_text/en/, accessed 30 May 2015).

[10] To exemplify this trend and consequent shifts in health, WHO has been coordinating initiatives such as the "World Health Day" and "Urban Health".

[11] World Health Organization. Urban health. (http://www.who.int/topics/urban_health/en/, accessed 30 May 2015).

Much of the natural and migration growth in urban populations is among the poor. More than 1 billion people – one third of urban dwellers – live in slum areas, which are often overcrowded and are affected by life-threatening conditions (UNDP 2005). In low-income countries, disparities will continue to rise as the combination of migration, natural growth and scarcity of resources makes it more difficult to provide the services needed by city dwellers (UN-Habitat 2013).[12] Poorly planned or unplanned urbanization patterns also have negative consequences for the health and safety of people, including decreased physical activity and unhealthy diets, which lead to increased risks for NCDs such as heart disease, cancer, diabetes and chronic lung disease (WHO 2010).

Urbanization also creates new challenges for biodiversity conservation; the development of cities is one of the most important drivers of land-use change.[13] Moreover, it was estimated that up to 88% of protected areas likely to be affected by new urban growth are in countries of low-to-moderate income (McDonald et al. 2008). While cities typically develop in proximity to the most biologically diverse areas (Seto et al. 2011), relatively little attention has been paid to how cities can be more biodiverse or to the importance of maintaining biodiverse ecosystems for human health (Andersson et al. 2014). Several health benefits can potentially be derived from integrating biodiversity into urban planning schemes, and broader conservation and public health policies.

5. INTEGRATING BIODIVERSITY AND HUMAN HEALTH: APPROACHES AND FRAMEWORKS

In large part, the biodiversity and health sectors have worked separately to achieve their respective goals. To better integrate biodiversity and health in research and policy, the adoption of multidisciplinary approaches that incorporate contributions from both the social and natural sciences is needed. The EcoHealth, One Health and "one medicine" approaches are part of a family of approaches that aim to bridge human health and the health of other species or ecosystems (whether defined as disease outcomes, and/or the functioning of an ecosystem/provisioning of its services) to address complex challenges faced by the global health and environmental communities. In this volume, they are referred to as "One Health approaches".

They are also closely related to the ecosystem approach adopted under the CBD.[14] While evolving from different sectors (the one medicine approach from veterinary and human medicine, with a focus on comparative medicine and links between livelihoods, nutrition and health; the Ecosystem and EcoHealth approach from the ecology and biodiversity communities, focusing on ecosystem, societal and health links; and the One Health approach primarily from conservation medicine, with a focus on public and animal health, development and sustainability) (Zinsstag et al. 2011), at their core they share the common goal of a more comprehensive understanding of the ecosystem-based dynamics of health (e.g. socioecological systems) than can be yielded through a single-species perspective alone. Given the integral links between biodiversity and human health, these approaches consider the connections between humans, animals and the environment, and can thus promote a more complete understanding of mutual dependencies, risks and solutions. These perspectives allow us to move beyond single-silo viewpoints (e.g. human or veterinary medicine exclusively) to a broader and more upstream consideration of the drivers, detection, control and prevention of disease.

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[12] World Health Organization. WHO Global Health Observatory (GHO) data: urban population growth. (www.who.int/gho/urban_health/situation_trends/urban_population_growth_text/en/, accessed 30 May 2015).

[13] For each new resident, rich countries add an average of 355 square meters of built-up area, middle-income countries 125 square meters, and low-income countries 85 square meters (McDonald et al. 2008).

[14] https://www.cbd.int/ecosystem/

The value of One Health approaches is increasingly being appreciated for infectious disease prevention and control, seeing application for zoonotic diseases such as avian influenza and rabies (Gibbs et al. 2014), and based on the overlapping drivers of disease emergence and spread and biodiversity loss, as well as domestic animal–wildlife and human transmission cycles (GBO3; Jones et al. 2008). In addition, One Health and Ecosystem approaches have wider potential applications and benefits, including the following:

1) to help inform our understanding of the health services provided by biodiversity, as well as how anthropogenic changes to an ecosystem or biodiversity may impact disease risks. Ecosystems may provide health-benefiting functions, such as toxin remediation by filtration mechanisms in wetlands (Blumenfeld et al. 2009). These functions and their underlying mechanisms may be missed when focusing on a single species;

2) to provide important knowledge for conservation and agricultural efforts, given the impacts of disease on agricultural and wild species. Several disease risks for human and domestic animals also pose risks for biodiversity; for example, while primarily maintained by domestic dogs, wildlife represents the majority of species susceptible to rabies, with some wild canid populations suffering severe declines from the disease (Machalaba and Karesh 2012);

3) for assessment of environmental health exposures and outcomes; in addition to being possible links in the food chain, wildlife may serve as sentinels for ecosystem changes and potential human risks, as seen with Ebola (Karesh and Cook 2005) as well as toxin exposures (Buttke 2011). As shown in Figure 1, this may lead to earlier detection and possible prevention and mitigation opportunities (Karesh et al. 2012).

Implementation of a One Health approach brings multiple sectors together to view our shared health across an ecosystem or specific disease challenge. Employing multispecies disease surveillance or risk analysis, with data sharing across human, agriculture and environment experts, can help move from our currently reactive public health measures to more preventive actions; similarly, this may benefit biodiversity and maintenance of ecosystem services through consideration of another potential aspect of impacts to an ecosystem.

Involvement of the social sciences, including disciplines such as economics and anthropology, can help to further address socioecological challenges, incorporating the social as well as environmental determinants of health. Synergies across these and other sectors may lead to cost–effective and more upstream disease prevention and management strategies, as well as have implications for biodiversity. In addition to interdisciplinary and cross-sectoral collaboration, addressing the common challenges faced by the global health and biodiversity conservation communities also necessitates the engagement of many stakeholders, including governments, civil society, nongovernmental and international organizations, as well as indigenous peoples and local communities. Through integrated approaches such as the One Health approach, researchers, practitioners, policy-makers and other stakeholders are better able to unravel the intricate web of challenges that they jointly face, and generate new insights and knowledge to find common solutions or, when these are not possible, carefully assess and manage trade-offs (Romanelli et al. 2014a,b).

Recently, the Intergovernmental science-policy Platform for Biodiversity and Ecosystem Services has developed a conceptual framework linking biodiversity, ecosystem services and human well-being (Díaz et al. 2015 a,b). The framework draws upon the Millennium Assessment framework, but goes further in highlighting the role of institutions, and in explicitly embracing different disciplines and knowledge systems (including indigenous and local knowledge) in the co-construction of assessments of the state of the world's biodiversity and the benefits it provides to humans.

6. CONCLUSION: A THEMATIC APPROACH TO COMMON LINKAGES

There is a pressing need to better understand the relationship between biodiversity and public health, and this volume seeks to make a contribution to this imperative. We already know that biodiversity and corresponding ecosystem services, and public health intersect on numerous fronts and these linkages are further explored in each of the thematic sections that follow.

This demands an understanding of biodiversity's fundamental contribution to essential life-supporting services, such as air and water quality and food provision. It also requires mapping the role of biodiversity in human health on many other fronts, including nutritional composition; micro- and macronutrient availability and NCDs; its applicability in traditional medicine and biomedical research that relies on plants, animals and microbes to understand human physiology; and its relationship with processes affecting infectious disease reservoirs. We also need to further explore the role of microbial diversity in our internal biomes in human health and disease; the threats of IAS to ecosystems and human health; the positive feedback loops associated with climate change; and many other associations. Our current state of knowledge of these and other themes is explored in greater detail in each of the thematic sections included in Part II of this technical volume.

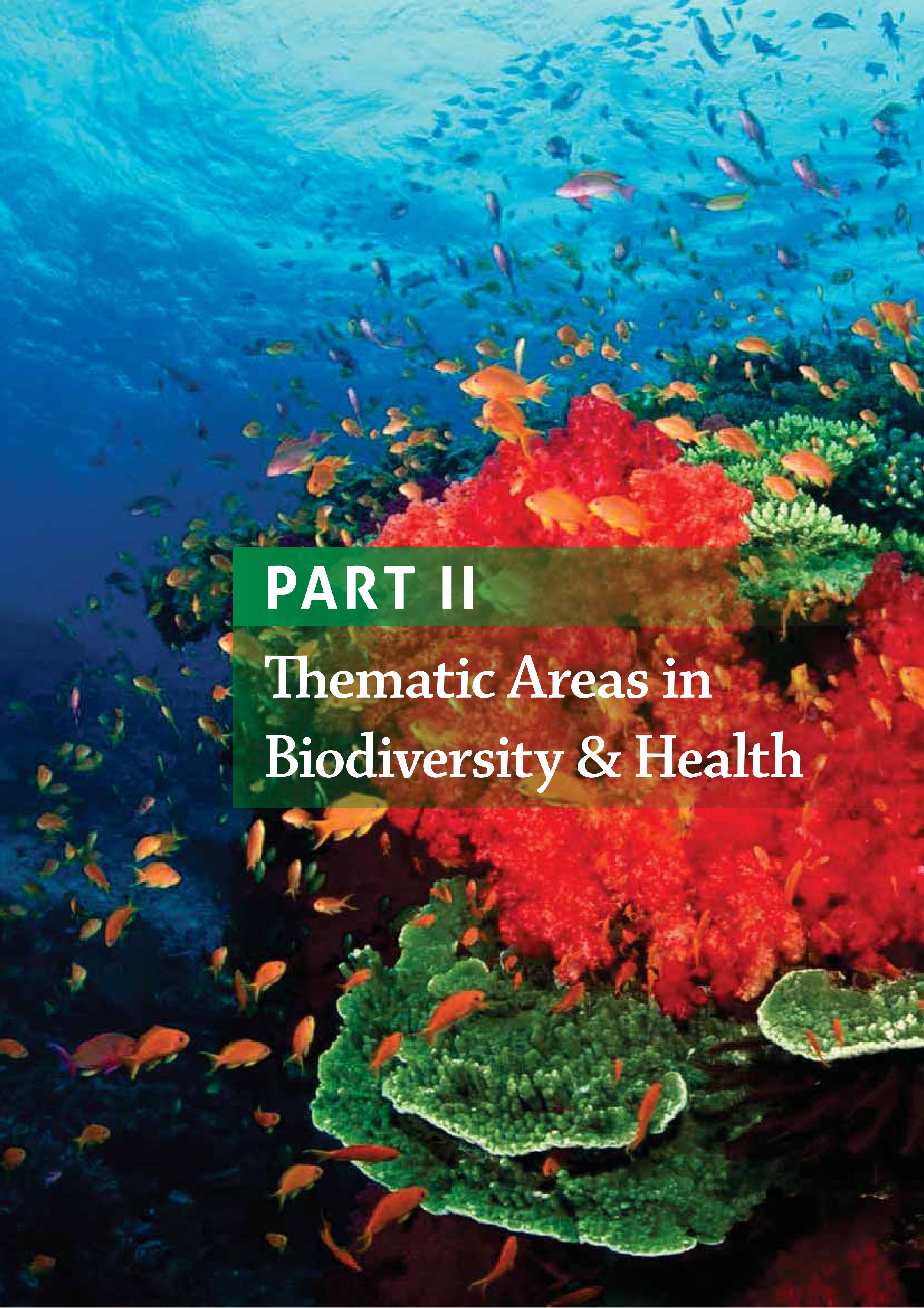
While there has been considerable scientific progress in understanding these linkages, much more interdisciplinary and cross-sectoral work is needed to assess the full breadth of causal links between environmental change, biodiversity, ecosystem processes and services, and the ultimate impacts on human health, which are not easily reduced to simple causal chains. These links are frequently non-linear[15] (Kremen 2005), difficult to predict, and are sometimes irreversible as biotic–abiotic interactions largely occur at the level of ecological processes rather than in the delivery of the services themselves[16] (Carpenter et al. 2009; Mace 2012). The difficulties inherent in determining these causal links in no way diminishes the importance of seeking to identify them.

Understanding the links between the weakening of ecosystem services and human health is essential to shaping robust policies, expanding our scientific understanding of the health needs of human communities, and to meeting new and existing challenges to public health in the face of global environmental change (McMichael and Beaglehole 2000).

Although the links between biodiversity and human health are fundamental, they are often diffused in space and time, and there are a number of actors that moderate the critical underlying relationships. To date, work at the biodiversity–health nexus has been insufficient, which may at least in part be explained by these diffuse links. While One Health and similar approaches have begun to garner greater international acceptance, the primary focus of interventions in the public health sector continue to tend toward curative interventions rather than preventive (upstream) interventions, which also consider the social and environmental determinants of health. A powerful argument can be made for the critical need to incorporate these dimensions to improve public health outcomes.

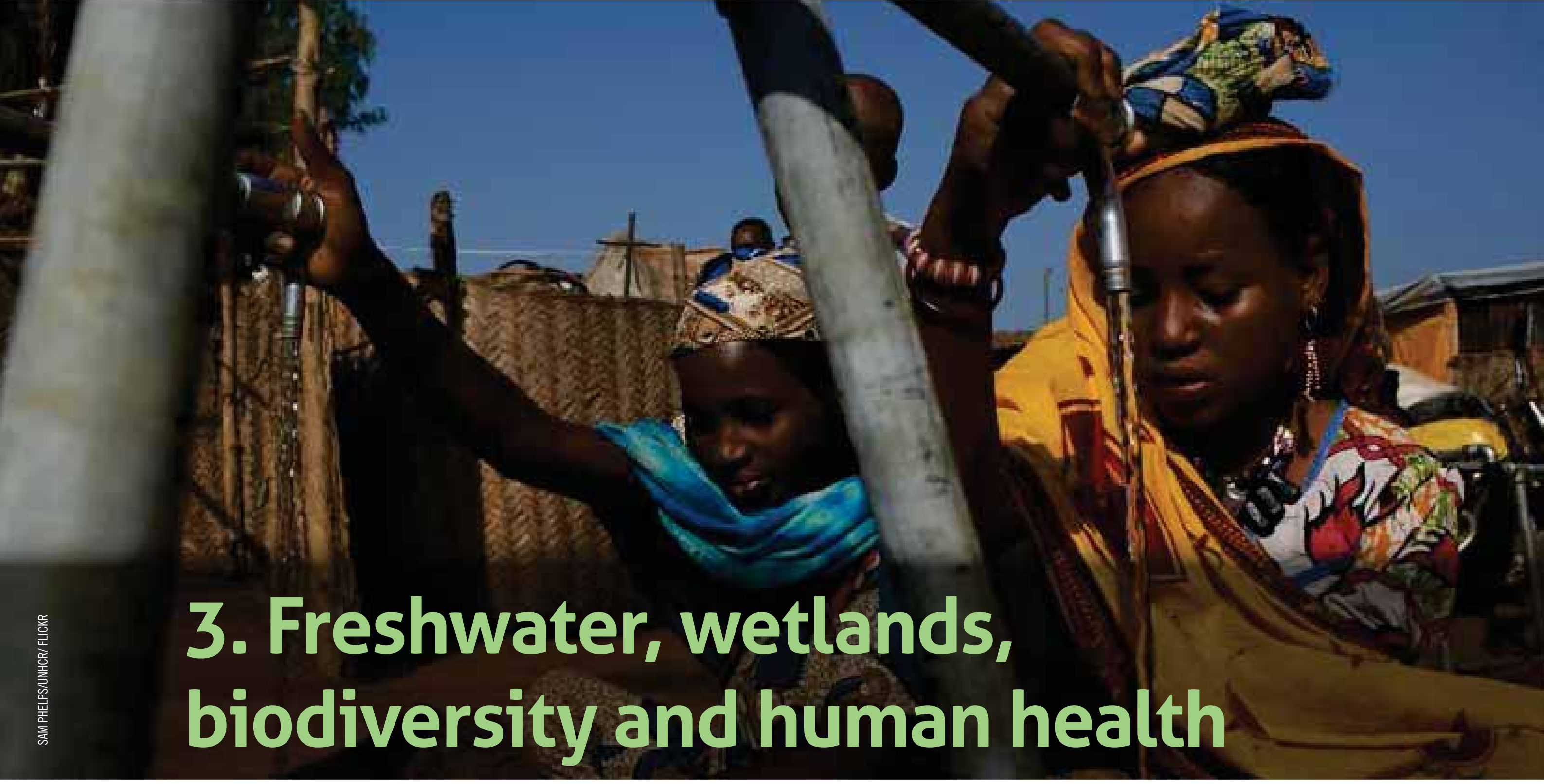
[15] As Carpenter et al. (2009) have noted, some drivers may affect human health without affecting biodiversity or the services it provides, or some ecosystem processes may affect drivers directly.

[16] This difficulty has been attributed to the fact that causal links can be non-linear or bypass some processes altogether.



PART II

Thematic Areas in Biodiversity & Health


SAM PHELPS/UNHCR/ FLICKR

3. Freshwater, wetlands, biodiversity and human health

1. Introduction

The centrality of water to human and ecosystem health is readily apparent, yet often neglected. Manipulating and adapting to changes in water levels – dealing with water scarcity, flooding or storms – has been instrumental for civilizational survival, and this will continue as climate change proceeds. The immense demand for water posed by modern industry, agriculture, aquaculture, forestry, mining, energy generation and human consumption combine to exacerbate pressures on water quality and quantity. Such threats to freshwater and other aquatic ecosystems cannot be viewed in isolation from their impacts on human health and well-being (Carr and Neary 2008).

In addition to direct health impacts (such as water-related illnesses), degradation caused by human activity (such as unsustainable agricultural practices) also affects access to sanitation, increases the time invested in reaching water resources, and hinders the capacity for local food production. Based on recent World Health Organization (WHO) estimates, some 768 million people, the majority from low-income countries, still rely on unimproved water supplies that are believed to have high levels of pathogen contamination (WHO 2013; WHO and UNICEF 2012; Prüss-Ustün et al. 2014).[1] This reinforces the ongoing importance of ensuring freshwater quality and supply from natural ecosystems for the control and regulation of waterborne and water-related diseases, in particular for the world's poorest, most vulnerable populations, who already carry a disproportionate portion of the global burden of disease.

As discussed in this chapter and in the wide breadth of scientific research in this area, the ecosystems that sustain our water resources are complex, and the often irreversible harm that they sustain can be linked to public health outcomes. More judicious management and use of our water resources and aquatic ecosystems, coupled with improved access to clean water, sanitation and safe energy sources are critical, intimately related goals (and challenges). As the last section of this chapter reiterates, these will demand the application of a holistic, cross-sectoral approach, such as the ecosystem or One Health approach, and equally integrated solutions that transcend disciplinary, sectoral and political boundaries.

[1] As defined by the WHO/UNICEF Joint Monitoring Programme for Water and Sanitation (Prüss-Ustün et al. 2014).

2. Water resources: an essential ecosystem service

Freshwater is a provisioning ecosystem service (MA, 2005a) and is important for several aspects of human health. All terrestrial freshwater ecosystems, forests, wetlands, soil and mountain ecosystems play a role in underpinning the water cycle, including regulating nutrient cycling and soil erosion (Russi et al. 2012; Coates and Smith 2012), and managing pollution (Schwarzenbach et al. 2010; Horwitz et al. 2012). Many of the world's major rivers begin in mountain highlands, and more than half of the human population relies on fresh water flowing from these areas (MA 2005b). It has been estimated that mountain ecosystems contribute between 32% and 63% to the mean annual river basin discharge, and supply around 95% of the total annual river discharge in some arid areas (Viviroli et al. 2003). Biodiversity is central to the ecological health of mountain ecosystems and river basins.

Water and soil conservation services of forests vary among biomes, landscapes and forest types. In many regions, forests improve surface soil protection and enhance soil infiltration, prevent soil erosion and landslides, protect riverbanks against abrasion, and regulate microclimate (CBD 2012; Naiman and Décamps 1997). For example, cloud forests can increase dry season flow and total water yield (see e.g. Hamilton 1995; Bruijnzeel 2004; Balmford and Bond 2005). Natural forests enhance river water quality by preventing soil erosion, trapping sediments, and removing nutrient and chemical pollutants, reducing microbial contamination (fecal coliform bacteria, cryptosporidium, fungal pathogens) of water resources, and preventing salinization (Cardinale et al. 2012; CBD 2012). Analyses of flood frequency in low-income countries have found that the slope, amount of natural/non-natural forest cover and degraded area explain 65% of variation in flood frequency (Bradshaw et al. 2007), and is linked to the number of people displaced and killed by such events, though associations with larger flooding events linked to extreme weather are not conclusive (van Dijk et al. 2009). This has implications for the development of improved disaster risk reduction strategies (see also the chapter on resilience and disaster risk reduction in Part III of this volume).

It is widely accepted that water purification services provided by biodiverse ecosystems underpin water quality, which is a universal requirement for maintaining human health. For example, the hydrological, chemical and biological processes of wetlands significantly ameliorate water quality.[2] Groundwater is also a major source of water for drinking and/or irrigation but also a potential source of pathogenic microorganisms (Gerba and Smith 2005; Lapworth et al. 2012). While biodiversity, including species diversity, may be a source of disease emergence, in some cases, high species diversity in vertebrate hosts of vectors can play a beneficial role by impeding dominance by particular species that act as key reservoirs of the pathogens (Ostfeld and Keesing 2000).[3]

2.1 The role of species diversity

The loss of species hinders the ability of ecosystems to provide ecosystem services such

[2] For example, based on a thorough review of 169 studies examining hydrological functions of wetlands, Bullock and Acreman (2003) reported that (1) wetlands significantly influence the global hydrological cycle, (2) wetland functions vary among different wetland hydrological types, (3) floodplain wetlands reduce or delay floods, (4) some wetlands in the headwaters of rivers increase flood flow volumes, sometimes increasing flood peaks, (5) some wetlands increase river flows during the dry season, and (6) some wetlands, such as floodplain wetlands hydrologically connected to aquifers, recharge groundwater when flooded. Mangrove wetlands are also effective in removing heavy metals from water (Marchand et al. 2012).

[3] Increased species diversity can reduce disease risk in some cases by regulating the abundance of an important host species (Rudolf & Antonovics 2005), or by redistributing vector meals in the case of vector-borne diseases (Van Buskirk and Ostfeld 1995; Norman et al. 1999; LoGiudice et al. 2003). In practice, transmission reduction can occur when adding species reduces pathogen load or the pathogen's titre (i.e. the concentration of an antibody, as determined by finding the highest dilution at which it is still able to cause agglutination of the antigen) within the host (Keesing et al. 2006). For a more thorough review on the role of biodiversity in disease emergence, see the chapter on infectious diseases in this volume.

as the filtering of pollutants. Numerous scientific studies have shown that filter feeders play an important role in the elimination of suspended particles from water and its purification (Newell 2004; Ostroumov 2005, 2006). Bivalve molluscs of both marine and freshwater environments have the ability to filtrate large amounts of water (Newell 2004; Ostroumov 2005). It has also been found that molluscs may reduce pharmaceuticals and drugs of abuse from urban sewage (Binellia et al. 2014). The mussel species *Diplodon chilensis chilensis* (Gray 1828), Hyriidae, native of Chilean and Argentinean freshwater habitats, play a key role in reducing eutrophication, both by reducing total phosphorus (PO_4 and NH_4) by about one order of magnitude and also by controlling phytoplankton densities. These mussels also contribute to increasing bottom heterogeneity and macrocrustacean abundance, and attract predatory fish. Thus, the mussels provide energy and a nutrient source to the benthic and pelagic food webs, contributing to more rapid recycling of organic matter and nutrients (Soto and Mena 1999).

Economic valuations of water as a habitat for freshwater species diversity have been carried out.[4] The first estimate of the global values of ecosystem goods (e.g. food in the form of aquatic species), services (e.g. waste assimilation), biodiversity and cultural considerations yielded a value of US$ 6579 x 109/year for all inland waters, exceeding the worth of all other non-marine ecosystems combined (US$ 5740 x 109/year), despite the far smaller extent of inland waters (Costanza et al. 1997). It follows that biodiversity conservation or restoration can be an effective, efficient and cost–effective way of improving water quality and wastewater management. Plant and algae species diversity enhances the uptake of nutrient pollutants from water and soil (e.g. Cardinale et al. 2012), and some animals (such as copepod *Epischura baikalensis* in Lake Baikal, Russia; see Mazepova 1998) and plant species enhance the purity of water. For example, *Moringa oleifera* seeds and *Maerua decumbens* roots are used for clarifying and disinfecting water in Kenya (PACN 2010). Yet, habitat degradation and biodiversity loss often continue to hamper the ability of ecosystems to provide water purification services and to decrease the quality of water available.[5]

2.2 Social costs of impaired water quality

Ecosystems play an essential role in regulating water quantity and quality, which are also primary factors affecting food production, essential for sustaining human health and livelihoods. For example, wetlands directly support the health and livelihood of many people worldwide through the provision of important food items such as rice and fish (Horwitz et al. 2012). There are multiple mental health benefits of experiencing a natural environment, including, for example, the contribution of spiritual and recreational values of wetlands to human psychological and social well-being (see also chapter 12 in this volume).

Impaired water quality results in significant social and economic costs, and ecosystem degradation is a major cause of declines in water quality. Rectifying poor-quality water through artificial means (such as water treatment plants) requires substantial investment and operational costs. Left untreated, poor-quality water results in massive burdens on human health, with women, children and the poor being the most affected. Reflecting this priority, many protected areas and special reserves have also been established to protect water supplies, including fresh water for urban areas (Blumenfeld et al. 2009). For example, 33 of 105 of the world's largest cities source their clean water from protected areas (Ervin et al. 2010; see also Box 1).

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4 Some of these studies also indicate that the services that such diversity provides are an essential driver of behavioural change. See the section on behavioural change in the chapter on Sustainable Development Goals and the post-2015 Development Agenda in Part III of this volume.

5 Moreover, while water quality can be monitored through chemical analysis, long-term trends in freshwater ecosystems may be best monitored using the diversity of aquatic organisms (such as benthic invertebrates) as proxy indicators for measuring water quality and ecosystem health.

Box 1. The Catskills: an ecosystem service for over 10 million people

The Catskills mountains were named a forest reserve in 1885 and are one of several important examples of the fact that cost–effective biodiversity and health co-benefits are achievable. In the three decades that followed the creation of the forest reserve, the high value of the life-supporting services provided by the mountains became apparent; rather than investing large sums of money on filtering water supplies, the state of New York invested in creating reservoirs in the Catskills park, beginning with the Ashokan Reservoir in 1898. Today, the New York watershed provides the largest unfiltered water supply in the United States and provides an estimated 1.3 billion gallons of drinking water to over 10 million residents daily. To this day, water quality standards mandated by the United States (US) Environmental Protection Agency have been met without the need for water filtration services, whose estimated costs would have run into billions of US dollars. It has been estimated that New York city avoided $6–8 billion in expenses over a 10 year period, by protecting its watersheds.

More recently, the important role of the Catskills as a breeding site for fish has also been recognized. The Catskill Center for Conservation and Development was founded in 1969, and has been advocating for the park since. To this day, the Catskills provide much of New York State's highest-quality drinking water as well as a relaxing recreational site for tourists and locals alike. Efforts to ban high-volume hydraulic fracturing for shale oil in the surrounding areas stem from concerns about its impact on water quality. There are also serious concerns about the potential of drought related to climate change having a significant impact on this vital ecosystem service.

Sources: Frei et al. 2002; MA 2005a; see also http://www.catskillmountainkeeper.org/no_time_to_stop_on_fracking

3. Dual threats to freshwater ecosystems and human health

Altered waterways and human development (e.g. construction of dams, irrigation canals, urban drainage systems, encouraging settlements close to water bodies) can all provide benefits to human communities. However, related infrastructure may not only be costly to build and maintain, but is also often accompanied by new risks to the environment (e.g. flood risk from degradation of coastal wetlands) and public health, including emergence of disease (Horwitz et al. 2012; Myers and Patz, 2009).[6] These activities can diminish native biodiversity and increase waterborne or water-related illnesses, such as schistosomiasis or malaria (discussed in section 3; see also chapter on infectious diseases in this volume), including neglected tropical diseases such as trachoma, onchocerciasis (Hotez and Kamath 2009), lymphatic filariasis (Erlanger et al. no date), or guinea-worm disease (Fenwick 2006).

Freshwater ecosystems, such as rivers, lakes and wetlands, face disproportionately high levels of threats to biodiversity due largely to demands on water (for a recent comprehensive review of the state of the world's wetlands and their services to people, see Garner et al. 2015). In some regions, up to 95% of wetlands have been lost and two thirds of the world's largest rivers are now moderately to severely fragmented by dams and reservoirs (UNEP 2012). Freshwater species have declined at a rate faster than any other biome, with the

[6] Waterborne diseases have been classified into four types: those spread through contaminated drinking water such as cholera; those linked to poor sanitation such as typhoid; those transmitted by vectors reliant on freshwater bodies for at least one stage in their life-cycles, such as malaria; and those that involve an aquatic animal to serve as an intermediate host, such as schistosomiasis (e.g. Resh 2009).

sharpest decline in tropical freshwater biomes.[7] More than one third of the accessible renewable freshwater on earth is consumptively used for agriculture, industrial and domestic purposes (Schwarzenbach et al. 2006), which often leads to chemical pollution of natural water sources, a cause for major concern in many parts of the world (Schwarzenbach et al. 2010). It has been estimated that approximately 67% of global water withdrawal and 87% of consumptive water use (withdrawal minus return flow) is for irrigation purposes (Shiklomanov 1997; see also Box 2 case study on cotton). This has drained wetlands, lowered water tables and salinized water sources through intrusion and diminished water flows in key river systems; some of these, such as the Colorado delta (Glenn et al. 1996) and Yellow river, China (Chen et al. 2003) now periodically fail to reach the sea. The oceans are similarly challenged: an estimated 38% decline in coral reefs has occurred since 1980, largely as a result of climate change, which is also causing changes in ocean habitat and sea levels, concurrent with ocean acidification (UNEP 2012).

As discussed in the subsections that follow, threats to water resources and ecosystems (both freshwater and marine) often present equally significant threats to human health. Other human activity, such as the use of pharmaceuticals or antibiotics, dam construction and mining activities also have significant direct and indirect, albeit unintended, consequences on water resources and public health. Ecotoxicological data on environmental exposure to pharmaceuticals and persistent substances such as anti-inflammatory drugs, antiepileptics, beta-blockers, antidepressants, antineoplastics, analgesics and contraceptives indicate a range of negative impacts on freshwater resources, ecosystems, living organisms and, ultimately, some aspects of human health (see Santos et al. 2010; Lapworth et al. 2012). The use of sex hormones and veterinary growth hormones can lead to bioaccumulation, and have been linked to endocrine disruption (Caliman and Gavrilescu 2009) and reproductive dysfunction (Khan et al. 2005), all of which pose dual threats to biodiversity and to the health of people who are reliant on freshwater resources (see also chapter on biodiversity, health care, and pharmaceuticals in this volume). As discussed in subsection 3.4, other causes of bioaccumulation include human activities such as mining.

3.1: Eutrophication, human health and ecosystem health[8]

Eutrophication, caused by the input of nutrients in water bodies and characterized by excessive plant and algal growth, is both a slow, naturally occurring phenomenon and a process accelerated by human activity (cultural eutrophication). The latter is caused by excessive point source (from a single identifiable source of contaminants) and non-point source (without a specific point of discharge) pollution; the most common causes include leaching from fertilized agricultural areas, sewage from urban areas and industrial wastewater.

The input of nutrients most commonly associated with eutrophication – phosphorus (e.g. in detergents) and nitrogen (e.g. agricultural run-off) – into lakes, reservoirs, rivers and coastal marine ecosystems, including coral reefs, have been widely recognized as a major threat to both water ecosystems and human health. In freshwater environments, cultural eutrophication is known to greatly accelerate algal blooms. In marine and estuarine systems, the enhanced inputs of phosphorus and nitrogen often result in a rise of cyanobacteria and dinoflagellates. The effects of eutrophication include the following:

- toxic cyanobacteria poisonings (CTPs)

[7] Based on data on the freshwater Living Planet Index (LPI), the decline in freshwater species was greater than any other biome between 1970 and 2008, although global terrestrial marine indices have also sharply declined. The freshwater LPI considers 2849 populations of 737 species of fish, birds, reptiles, amphibians and mammals found in temperate and tropical freshwater lakes, rivers and wetlands. Among them, tropical freshwater species declined more than any other biome. Data prior to 1970 are not captured due to insufficient data (WWF 2012). For further discussion on the global status of species declines, see also Global Biodiversity Outlook, fourth edition (CBD 2014).

[8] Shaw et al. 2003; Carmichael, 2001; EEA 2005; Shaw and Lam 2007; Chorus and Bartram 1999; WHO 1999

- increased biomass of phytoplankton and macrophyte vegetation
- increased biomass of consumer species
- shifts to bloom-forming algal species that might be toxic or inedible
- increase in blooms of gelatinous zooplankton (marine environments)
- increased biomass of benthic and epiphytic algae
- changes in species composition of macrophyte vegetation
- decline in coral reef health and loss of coral reef communities
- increased incidence of fish kills
- reduction in species diversity of harvestable fish and shellfish
- water treatment and filtration problems
- oxygen depletion
- decreases in perceived aesthetic value of the water body.

It was found that eutrophication occurs in approximately 54% of Asia-Pacific, 53% of European, 48% of North American, 41% of South American and 28% of African lakes. Eutrophication can cause considerable harm to freshwater, marine ecosystems, and terrestrial ecosystems and the life that inhabits them; these impacts can range from wild and domestic animal illness and death to equally far-ranging consequences for human health. For example, in 1996, a routine haemodialysis treatment at a dialysis centre in Caruaru, Brazil led to an outbreak of cyanotoxin human toxicosis. Among 130 patients affected, almost 90% experienced visual disturbances, nausea and vomiting, 100 of them developed acute liver failure and 70 died; 53 of these deaths were attributed to what is now known as the "Caruaru syndrome."

Medical facilities are only one of several potential routes of exposure to human toxicity from cyanotoxins; others include the recreational use of lakes and rivers, and the consumption of drinking water, algal dietary supplements and food crops, among others. In addition to Brazil, health problems attributed to the presence of cyanotoxins in drinking water have been reported in a number of countries, including Australia, China, England, South Africa and the United States.

3.2 Proliferation of cyanobacteria caused by eutrophication

The discharge of nutrients in waterways can lead to eutrophication. Under eutrophic conditions, nutrient loading indirectly decreases the amount of oxygen in the water and eventually eliminates certain species. In oxygen-depleted water, fecal pathogens may proliferate and the risk of enteric disease transmission increases (Fuller et al. 1995). In addition, wherever conditions of temperature, light and nutrient status are conducive, surface waters may host increased growth of algae or cyanobacteria. This phenomenon is referred to as an algal or cyanobacterial bloom (see section 3.1). Problems associated with cyanobacteria are likely to increase in eutrophic areas, such as those with high sewage discharge and agriculture practices (WHO 1999). Species of cyanobacteria may produce toxins that affect the neuromuscular system and liver, and can be carcinogenic to vertebrates, including humans.

Among the 14 000 species of continental algae, about 2000 are cyanobacteria and 19 genera produce toxins. Cyanotoxins show specific toxic mechanisms in vertebrates, some of which are strong neurotoxins (anatoxin-a, anatoxin-a(s), saxitoxins) and others are primarily toxic to the liver (microcystins, nodularin and cylindrospermopsin). Microcystins are geographically most widely distributed in freshwaters (WHO 1999). They bioaccumulate in common aquatic vertebrates and invertebrates, including fish, mussels and zooplankton (Ibelings and Chorus 2007). Cases were reported in the Latin American and Carribbean region. For example, in

a hypertrophic reservoir in Argentina, if a 70 kg person would consume 100 g of fish (*Odontesthes bonariensis*), the equivalent of approximately 0.49 mg/kg body weight/day would be consumed (Cazenave et al. 2005), which is in excess of the range of the seasonal tolerable daily intake (TDI) (0.4 mg/kg/day). In Brazil, concentrations of microcystins in edible parts of *Tilapia rendalli* were examined during the cyanobacterial bloom season. Concentrations varied between 0.0029 and 0.337 mg/g muscle tissue. Consumption of 300 g of fish with this highest concentration would exceed the seasonal TDI by four times. The amount of toxin in Tilapia livers has been found to reach levels as high as 31.1 mg/g wet weight (Freitas de Magalhães et al. 2001), so that in a typical meal, an adult could be exposed to hundreds of times the seasonal TDI. Common advice given by water authorities is that the viscera of the fish should not be eaten, but caution should be exercised in all cases where major toxic blooms occur.

Where bloom formation is well characterized in terms of annual cycles, the health risk may similarly be low if control measures are in place for times of bloom formation. If regular monitoring of source phytoplankton is in place, waters presenting no significant cyanotoxin risk may be easily identified (see review in WHO 1999). Substantially less is known about the removal of neurotoxins and cylindrospermopsin than about microcystins, thus toxin monitoring of treatment steps and finished water is especially important. Methods such as adsorption by some types of granular activated carbon and oxidation can be effective in cyanotoxin removal (WHO 1999).

3.3 Multiresistant bacteria: new approaches in sewage treatment

The use of antibiotics in hospitals, for swine and poultry production, and in fish farms can result in routes of dissemination of multiresistant bacteria and their genes of resistance into the environment, thus contaminating water resources and having a serious negative impact on public health. Antibiotics are widely used to protect the health of humans and domesticated animals, and/

or to increase the growth rate of animals as food additives. The use of antibiotics may accelerate the development of antibiotic resistance genes (ARGs) in bacteria and other pathogens, which pose health risks to humans and animals (Kemper 2008; see also the chapter on health care and impact of pharmaceuticals on biodiversity in this volume). The introduction of these new genes can alter the biology of pathogens because ARGs can be transmitted to other species of bacteria (Heuer et al. 2002; Tennstedt et al. 2003). Therefore, even common strains of pathogens may incorporate these genes and become resistant to antibiotics. The only way to detect multiresistant bacteria is by performing a DNA microarray. However, this kind of procedure is not yet common in health centres.

Perhaps the most effective and direct approach to reduce the possibility of the introduction and spread of ARGs is the controlled use of antibiotics in health protection and agriculture production. New and effective wastewater treatment processes are also needed to improve removal efficiency of ARGs in sewage treatment plants. Additionally, irrigation using wastewater has to be discussed thoroughly, considering possible introduction of ARGs in the soil and groundwater (Zhang et al. 2009).

3.4 Bioaccumulation: the impact of mining

Many mining activities discharge mercury (Hg) and methyl Hg in aquatic ecosystems, thereby contaminating water, ecosystems and aquatic species with a correspondingly negative repercussion on human health. (For a recent review of freshwater fish species in Africa please see Hannah et al. 2015.)

There are many ways by which Hg can reach aquatic ecosystems. Major anthropogenic sources are artisanal and small-scale gold-mining (ASGM) activities, which use Hg to amalgamate with gold (Veiga et al. 2014), and deforestation and burning of organic matter, which can remobilize Hg from the soil into the food chain (Passos and Mergler 2008). ASGM activities account for approximately 12% of all gold produced worldwide (Veiga et al. 2014), and to produce 1 mg of gold, 2.5–3.5 mg of Hg are used, of which approximately 50% reaches streams and rivers as suspended sediment (UNEP 2013). Metallic Hg is also emitted into the atmosphere as a result of ASGM activities, and is reduced into inorganic Hg and precipitated into terrestrial and aquatic ecosystems.

While Hg remains in the soil, it is often in its inorganic form, less toxic, but when it reaches water courses, microorganisms may transform it to a more toxic form, methyl Hg (Hacon and Azevedo 2006). Methyl Hg can bioaccumulate in the tissue of organisms and through the food chain, as they are consumed by other species. It can also reach human populations through fish consumption (Passos and Mergler 2008). In human populations, methyl Hg is neurotoxic and prenatal exposure can affect brain development, even at low doses of exposure[9]. Children exposed to methyl Hg may have delayed and impaired neurodevelopment, and exposed adults may have impaired motor coordination, visual fields, speech and hearing (UNEP, UNICEF, WHO 2002).

Methyl Hg was found in high concentrations in fish and shellfish, which are also the primary sources of exposure to human populations (Veiga et al. 1994; Porvari 1995; Fearnside 1999). In the Guri hydroelectric reservoir in Venezuela, from 219 fish samples, 93 specimens showed levels above 0.5 ppm Hg and up to 90% of the most appreciated piscivore fish in the region (*Rhaphiodon vulpinus*) showed average Hg levels of 2.7 ppm (0.17–8.25 ppm) (UNIDO 1996) – higher than those found in detritivorous and herbivorous fish species. Contamination through methyl Hg is particularly high in the Amazonian region. Several Amazonian communities have Hg levels considered to be critical for optimal neurological development. Dietary Hg intake has

[9] For a summary of the health impacts associated with mercury exposure and the identification of potential pathways for strategic action see also World Health Organization: http://www.who.int/phe/news/Mercury-flyer.pdf. For guidance on assessing the risk of mercury exposure to humans see also WHO-UNEP (2008), available at http://www.who.int/foodsafety/publications/chem/mercuryexposure.pdf?ua=1

been estimated to be 1–2 μg/kg/day, considerably higher than the WHO recommendation (0.23 μg/kg/day) (Passos and Mergler 2008).

The reduction or elimination of Hg use in ASGM has been receiving widespread attention (Veiga 2014). Less damaging options include amalgamating a gold concentrate rather than the whole ore and using "mercury-free artisanal gold", in which gold is isolated by centrifuges and the gangue materials magnetically removed (Drace et al. 2012). Awareness and education about Hg poisoning in ASGM communities is also essential to ensuring adherence to such changes in ASGM technology.

4. Impacts of agriculture on water ecosystems and human health

Unsustainable agricultural practices have significant impacts on human health, and water pollution from fertilizers, pesticides and herbicides remains a serious problem (see the chapter on agricultural biodiversity and food security in this volume). Better use of ecosystem services, underpinned by biodiversity, in agricultural production systems provides considerable opportunities to reverse these impacts on health while simultaneously improving food security.

Agriculture accounts for about 70% of global water use, and physical water scarcity is already a problem for more than 1.6 billion people (IWMI 2007). It is increasingly recognized that the management of land and water are inextricably linked (e.g. DEFRA 2004). In England, for example, up to 75% of sediment loading in rivers can be attributed to agriculture, while 60% of nitrate pollution and 25% of phosphates in surface waters originates from agriculture (DEFRA 2007). Agricultural practices can also contribute to the spread of water-related and waterborne disease. For example, significant *E. coli* loads have been found in run-off from land grazed by cattle and treated with livestock wastes (Oliver et al. 2005), all of which impact the quality of water for human consumption and use.

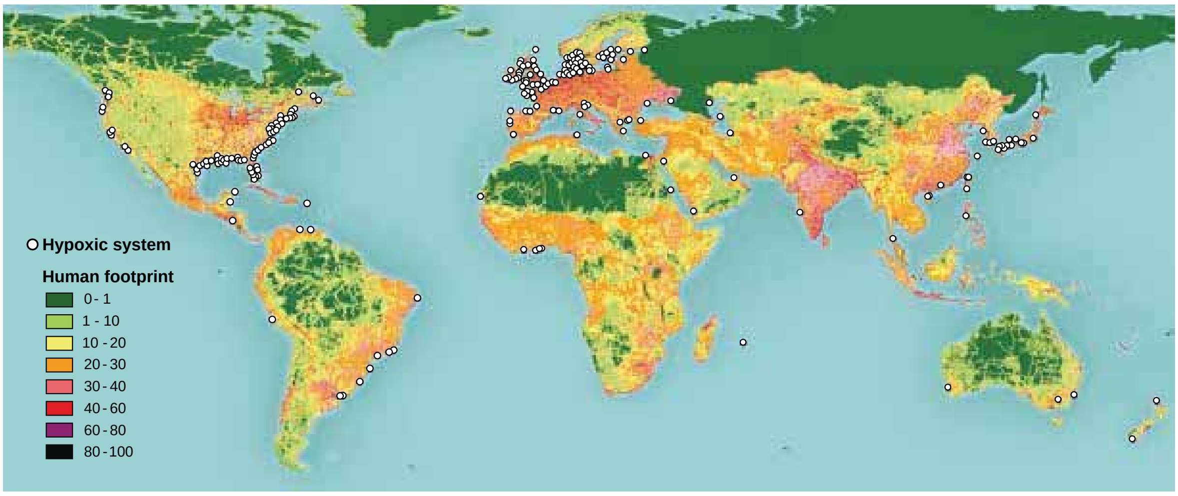
Natural vegetation cover in buffers along rivers is critical to the regulation of water flow, retention of nutrients, and capture of pollutants and sediments across landscapes (reviewed in Osborne and Kovacic 1993). The removal of trees and natural habitats in landscapes affects soil directly, as well as the quantity and quality of water draining from agricultural systems. Riparian buffers of non-crop vegetation are widely recommended as a tool for removing non-point source pollutants, particularly nutrients (nitrates, phosphorus, potassium) from agricultural areas, especially those carried by surface run-off (Lee et al. 2003; Brüsch and Nilsson 1993; Daniel and Gilliam 1996; Glandon et al. 1981; Nakamura et al. 2001). In field studies, even buffers of switchgrass along fields removed 95% of the sediment, 80% of the total nitrogen (N), 62% of the nitrate nitrogen (NO_3-N), 78% of the total phosphorus (P), and 58% of the phosphate phosphorus (PO_4-P). If the buffer included woody species, it removed 97% of the sediment, 94% of the total N, 85% of the NO_3-N, 91% of the total P, and 80% of the PO_4-P in the run-off (Lee et al. 2003).

Nutrient run-off from agricultural sources into waterways has been blamed for the production of hypoxia, popularly termed (aquatic) "dead zones" (Diaz 2001). These destroy local fisheries in many coastal areas, which communities rely on for the intake of protein and other nutrients. Dead zones have now been reported in more than 400 systems, affecting a total area of more than 245 000 square kilometres (Diaz and Rosenburg 2008; see Figure 1). These are concentrated along the eastern seaboard of North America, and European and Japanese coastlines, where human ecological footprints and agriculture intensities are highest (Diaz and Rosenburg 2008, see Figure 1).

Agricultural practice and its demand for water have reduced both the amount and quality of drinking water available for human consumption. At the same time, lack of irrigation in many low-income countries is a leading cause of poor crop production and yield gaps (Lobell et al. 2009). By 2002, irrigated agricultural land comprised less than one fifth of all cropped area but produced 40–45% of the world's food (Döll and Siebert

2002). Integrated water management practices that maintain and use biodiversity to support ecosystem services that improve water use efficiency and water quality will be needed to reduce the negative impacts of current water use practices on human health and contribute to its improvement.

FIGURE 1: Eutrophication-associated dead zones, 2008



Global distribution of over 400 systems that have scientifically reported accounts of being eutrophication-associated dead zones.
Source: Diaz and Rosenberg 2008

Box 2. Case study: Water consumption and cotton production

Cotton is a particularly important global crop and the most important natural fibre used in textile industries worldwide, accounting for 40% of textile production, but it is also a major consumer of water: over half of all cotton production is dependent on heavy irrigation (Soth et al 1999; Chapagain 2006). In the period 1960–2000, an environmental disaster unfolded as the Aral Sea in Central Asia lost approximately 60% of its area and 80% of its volume (Glantz 1998; Pereira et al. 2002) as a result of the annual withdrawal of water from its main feeder rivers, the Amu Darya and the Syr Darya, for cotton agriculture in the desert (Cosgrove and Rijsberman 2014). This depletion of water affected local fisheries and livelihoods (Micklin 2007), as well as water quality both from harvesting and processing (Bednar et al. 2002; Chapagain et al. 2006). As cotton is a global commodity, its consumption takes place in areas remote from its growth. One study concluded that about 84% of the "water footprint" of cotton consumption in Europe is located outside the continent, with "major impacts in India and Uzbekistan" (Chapagain et al. 2006).* Efforts to improve the production of cotton have focused on the development of transgenic *Bacillus thuringiensis* (Bt) cotton, which reduces insecticide use (Cattaneo et al. 2006), as well as improvements in water efficiency through drip irrigation furrow, and other efforts to reduce the negative environmental and human health impacts. Despite these efforts, cotton production, itself a source of agricultural biodiversity reduction, remains a major consumer of global freshwater with a pronounced impact on freshwater biodiversity.

* Whereas the term "ecological footprint" denotes the area (ha) needed to sustain a population, the "water footprint" represents the water volume (cubic metres per year) required, including dilution water necessary to restore polluted water to internationally agreed water quality standards.

5. Waterborne and water-related diseases

Long before the advent of modern medical care, industrialized countries decreased their levels of water-related disease through good water management. Yet, even in these countries, outbreaks of waterborne disease continue to occur, sometimes with lethal consequences. In developing countries, water-related disease blights the lives of the poor. Gro Harlem Brundtland, former WHO Director-General, 2001.

Surface freshwaters are among the most altered ecosystems on the planet and, coupled with associated biodiversity loss, have been linked to increased incidence of infectious diseases, including waterborne illnesses (Carpenter et al. 2011; see also the chapter on infectious diseases in this volume for a detailed discussion). Although the global disease burden of many formerly devastating waterborne illnesses (e.g. cholera, typhoid fever) has declined considerably, others continue to affect a significant proportion of the global population, especially in the world's lowest-income regions, such as sub-Saharan Africa, where the highest concentration of poverty occurs (Hotez and Kamath 2009).

The presence of pathogenic (disease-causing) microorganisms in freshwater can lead to the transmission of waterborne diseases,[10] many of which cause diarrhoeal illness, a leading cause of mortality in children under 5 years of age, and among the most prevalent waterborne illnesses, particularly in low- and middle-income countries (Prüss-Ustün et al. 2014; WHO 2013; WHO and UNICEF 2012; UNESCO 2009; Prüss-Üstün and Corvalán 2006).[11] Unsafe drinking water itself accounts for 88% of diarrhoeal disease worldwide (including cholera, typhoid and dysentery) and results in 1.5 million deaths each year, the majority of them among young children (Prüss-Üstün et al. 2008; WHO 2003a).[12]

Factors that have been found to increase the incidence of waterborne diseases include urbanization and high population densities of people, agriculture and industry (Patz et al. 2004). Habitat destruction or modification also plays a major role. For example, dam-related reservoir construction increases the prevalence and intensity of human schistosomiasis in Africa (e.g. N'Goran et al. 1997; Zakhary 1997) and elsewhere (Myers and Patz 2009), as described in Box 3. Climate change and the spread of aquatic invasive species (see section 5.1) may facilitate transmission of human pathogens (such as the Asian tiger mosquito *Aedes albopictus*) and can transmit viruses such as dengue, LaCrosse, West Nile and chikungunya (Benedict and Levine 2007).

A strong relationship between the human development index (HDI), access to drinking water services and sanitation with mortality by diarrhoea was found in some parts of the world, particularly low-income countries. Almost half of the population in these countries is at risk of exposure to waterborne diseases, including gastroenteric diseases such as dysentery, giardiasis, hepatitis A, rotavirus, typhoid fever and cholera. Less economically developed countries such as Haiti, for example, had the lowest water and sanitation coverage levels, coupled with the lowest HDI values and highest child mortality rates, in contrast to Chile, Costa Rica, Cuba and Uruguay, among others, which had higher values and coverage (PAHO 2012).

Human alteration of hydrological regimes has often been motivated by concerns for human health and well-being (Myers et al. 2013). While altered waterways (e.g. dams, irrigation canals, urban drainage systems) have indeed provided

[10] The contamination of surface waters with fecal material from humans, livestock or wildlife has been identified as an important (albeit not exclusive) pathway for the transmission of waterborne diseases (Prüss-Üstün and Corvalán 2006; US EPA 2003; Ragosta 2010).

[11] See also http://www.who.int/mediacentre/factsheets/fs330/en/; http://www.cdc.gov/healthywater/wash_diseases.html

[12] Children under 5 years of age living in poor dwellings with inadequate access to health services are the most susceptible to diarrhoeal disease and account for the overwhelming majority of all deaths attributed to these diseases (WHO 2004). Relatively little is known about the pathogens that account for diarrhoeal disease themselves (Yongsi 2010).

valuable benefits to human communities (e.g. energy, employment, access to food), they are costly to build and maintain, have frequently been accompanied by unintended consequences to ecosystems[13] and have had negative repercussions on public health, in some cases considerably increasing the availability of habitats for disease organisms and their vectors (de Moor 1994) and exacerbating waterborne disease outbreaks (Dudgeon et al. 2006; Hotez and Kamath 2009; Myers et al. 2014).

It has been estimated that some 2.3 billion people suffer from diseases related to water, and diseases transmitted by freshwater organisms kill an estimated 5 million people per year. Unsustainably managed ecosystems, such as wetlands, may harbour waterborne and vector-borne pathogens such as plasmodium and human schistosoma; the latter is described in Box 3 (Horwitz et al. 2012; Dale and Connelly 2012; Dale and Knight 2008; Fenwick 2006).

The habitat degradation that often accompanies human development activities, and corresponding simplification of natural species assemblages, have been found to foster the proliferation of disease vectors. The maintenance of natural freshwater communities and ecosystem integrity, where possible, may correspondingly contribute to a reduction in conditions for the transmission of diseases, including those related to water (Dudgeon et al. 2006). The development of dams and irrigation projects, for example, can contribute to expanding habitats for mosquitoes, aquatic snails and flies, which can spread disease among resettled agricultural populations. River damming changes physical and chemical conditions, altering the original biodiversity (Tundisi et al. 2002). Reduced water current creates favourable conditions for molluscs from the genus *Biomphalaria*, potential vectors of schistosomiasis. This disease affects over 200 million people worldwide, of which 88 million are under 15 years of age, with the heaviest infections being reported in the 10–14 years' age group in Africa and South America (UNEP, UNICEF & WHO 2002).

Other species, such as aquatic plants, are also affected by shifting environmental conditions, which in turn may favour mosquito breeding, including mosquitoes of the genus *Anopheles*, potential vectors of a protozoan – genus *Plasmodium* – causing malaria (Thiengo et al. 2005). Many studies have reported the increase in malaria cases after the construction of large dams. From the Chiapas hydroelectric power plant in Mexico to Itaipu Binacional in Brazil/Paraguay, thousands of malaria cases were linked to dam construction (Couto 1996). In South America, almost 60% of all reservoirs were built since the 1980s. Prevalence of other diseases may also increase with river damming. In the area of influence of the Yacyreta dam (Paraná River, Argentina/Paraguay), *Culicoides paraensis* mosquitoes were found (Ronderos et al. 2003). These are known vectors of Oropouche fever – which registered epidemics in many urban centres in the Pará State of Brazil (Barros 1990).

Biological and chemical threats (e.g. agricultural run-off, pharmaceuticals) to water resources, as well as the development of water-related infrastructure and urbanization, have also had their share of detrimental impacts on both biodiversity and human health by diminishing native biodiversity and sometimes increasing the potential for waterborne illnesses.

The global community has widely acknowledged the importance of access to clean water, sanitation and hygiene as critical development interventions

13 Human activities can hamper the ecological balance of wetlands and thereby alter existing disease dynamics or introduce novel disease problems (Horwitz et al. 2012). For example, flood risk may also increase as a result of degradation of coastal wetlands, demonstrated with Hurricane Katrina's impact on New Orleans, and extant deforestation exacerbated the health impact of the 2010 earthquake in Haiti.

in several goals and targets of the Millennium Development Goals (MDGs).[14] It was estimated that over one sixth[15] of the world's population did not have access to safe water at the time the MDGs[16] were adopted (Prüss-Üstün et al. 2004). While considerable progress had been achieved by 2010,[17] much work is still needed to meet global targets, particularly in low-income regions, including sub-Saharan Africa (WHO and UNICEF 2012). Subjacent to the fulfilment of these objectives is the need to sustainably manage the ecosystems that provide the critical life-supporting services that sustain our water (and other) resources.

The provision of clean water and sanitation to the world's poor, who are particularly vulnerable and ill-equipped to cope with further loss of ecosystem services, garners health benefits. The sustainable management of resources can also alleviate pressures caused by the unsustainable use of wetland and other ecosystems, reducing waste flows while also improving the overall quality of fresh and coastal waters essential to health and well-being.

Box 3. Ecosystem disturbance and waterborne disease: the case of schistosomiasis

While ecosystems can act as disease reservoirs, there is abundant scientific literature to support the claim that these cannot be viewed in isolation from the human activity that alters them. Schistosomiasis is a waterborne disease that affects some 200 million people worldwide. It can cause grave damage to internal tissues, including the liver, intestines and bladder, and has been found to undermine growth and development in children.

While schistosomiasis has been closely related to ecosystem disruption and the unsustainable use of biological resources, it is also sustained in a setting of poverty. A systematic review of schistosomiasis and water resource development carried out by Steinmann et al. (2006) estimated that among 200 million infected, an estimated 93% (192 million cases) occur in sub-Saharan Africa, including 29 million in Nigeria, 19 million in the United Republic of Tanzania, and 15 million each in the Democratic Republic of the Congo and Ghana. Approximately 76% of the population in sub-Saharan Africa lives near rivers, lakes and other contaminated water bodies.

Schistosomiasis is caused by parasitic worms (*Schisotoma* spp.), which spend a portion of their life-cycle in some species of freshwater snails that act as intermediate hosts for the disease. People become infected with the parasitic worms when they enter contaminated waters and the parasitic worms leave their host to penetrate human skin, thus infecting the subject. In Lake Malawi, it was found that overfishing caused an increase in abundance of *Bulinus nyassanus,* a snail species that acts as the intermediate host of the schistosome parasite.

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[14] See MDG 7 (Ensure environmental sustainability) Targets 9, 10, 11; MDG 4 (Reduce child mortality) Target 5; MDG 6 (Combat HIV/AIDS, malaria, and other diseases) Target 8.

[15] It is estimated that 1.1 billion people did not have access to safe drinking water and 2.4 billion lacked access to improved sanitation when these goals and targets were first adopted.

[16] When the MDGs were first adopted, approximately 3.1% of annual deaths (1.7 million) and 3.7% of the annual health burden of disability-adjusted life years (DALYs) worldwide (54.2 million) were attributed to unsafe water, sanitation and hygiene, all of them in low-income countries and 90% of them in children (WHO 2003). Major enteric pathogens in affected children include: rotavirus, *Campylobacter jejuni*, enterotoxigenic *Escherichia coli*, *Shigella* spp. and *Vibrio cholerae* O1, and potentially enteropathogenic *E. coli*, *Aeromonas* spp., *V. cholerae* 0139, enterotoxigenic *Bacteroides fragilis*, *Clostridium difficile* and *Cryptosporidium parvum* (Ashbolt 2004; WHO 2003a).

[17] By 2010, some 884 million people still did not use improved sources of drinking water (WHO 2010a). Additionally, 2.6 billion people did not use improved sanitation.

In Cameroon, schistosomiasis has been associated with an increase in deforestation. The increase in the amount of sunlight penetration, altered water rates and flow levels, and increase in vegetation growth caused by deforestation altered the ecology of freshwater snail populations in the area. *Bulinus truncatus,* a competent host for the parasitic worm *Schistosoma haematobium* (responsible for an estimated two thirds of all schistosoma infections in sub-Saharan Africa and an important cause of severe urinary tract disease), displaced another type of freshwater snail, *Bulinus forskalii*, which itself hosted a non-pathogenic schistosome but was less able to thrive in cleared habitat.

In Kenya, the prevalence of urinary schistosomiasis in children rose to a staggering 70% ten years after the start of the Hola irrigation project (prevalence was 0% prior to the start of the project). The irrigation project led to the introduction of a new snail vector well suited to the altered environment. The prevalence of schistosomiasis further increased to 90% by 1982. (Malaria is another disease that has been closely associated with the construction of dams and irrigation projects.)

In the Nile Delta of Egypt, dam construction in 1965 also led to an increase in schistosomiasis by increasing the habitat for *Bulinus truncates*, leading to an increase of almost 20% in the 1980s from 6% prior to dam construction. The increase in disease prevalence was even greater in other parts of the country.

Sources: Myers and Patz 2009 (and references therein); Evers 2006; Molyneux et al. 2008; Steinmann et al. 2006; Hotez and Kamath 2009.

5.1 Aquatic invasive alien species

Invasive alien species (IAS) are a major threat to biodiversity (Simberloff et al. 2005; McGeoch et al. 2010). Aquatic invasive species are among the most pernicious, often travelling across the globe before introduction. While some introductions are purposeful, such as the introduction of the Nile perch (*Lates niloticus)* to Lake Victoria, which has caused disastrous and irreparable harm, many others are incidental. The perch was introduced for commercial reasons, and it proceeded to dominate the lake and led to the extinction of up to 200 species of endemic haplochromine cichlids (Goldschmidt et al. 1993). Recent evidence suggests that there has been some recovery of aquatic biodiversity in the area, and that eutrophication also played a role in the mass extinction event recorded by observers in Lake Victoria, and that the Nile perch is now on the decline (Stearns and Stearns 2010; Goudswaard et al. 2008). While the introduction of alien species may sometimes be beneficial, the case of the Nile perch remains a very good example of how irreparable harm can be done to a complex ecosystem and why commercial introductions should be viewed with the utmost caution for potential consequences.[18]

In contrast, many aquatic invasives have arrived after surreptitiously travelling on cargo ships and oil tankers, which use ballast water to balance their hulls.[19] The zebra mussel worked its way into the North American Great Lakes via Russia

[18] Invasive species *Limnoperna fortunei* (Dunker 1857), Mytilidae, is considered as a major problem for hydroelectrical power plants because of their high growth rates, which obstruct the pipes. However, their filtering rates are among the highest for suspension-feeding bivalves, reaching as high as 125–350 ml individual–1 h–1. The high filtration rates, associated with the high densities of this mollusc (up to over 200 000 ind m–2) in the Paraná watershed – where there are many dams, including Itaipu Binacional, one of the largest in the world – suggest that its environmental impact may be swiftly changing ecological conditions in the areas colonized, which include four countries, Brazil, Paraguay, Uruguay and Argentina (Sylvester et al. 2005).

[19] Other means of accidental introduction include pet, aquaculture and aquarium releases or escapes, seaway canals, and even irresponsible research activities.

in 1986, while the comb jelly went in the opposite direction, from the United States (US) to the Caspian Sea, with devastating impacts on fisheries there (Chivian and Bernstein 2008: 49). The zebra mussel has had a complex impact on the water quality of the Great Lakes. While these bivalves can give lake water a clearer appearance as they filter various particles, including some forms of algae, they also consume phytoplankton (the building block of the marine food system), and they give harmful blue–green algae a competitive advantage, contributing to new dead zone growth.[20] Ricciardi (2006) estimated that one new species had been discovered in the North American Great Lakes every 28 weeks during the 1990s; while Cohen and Carlton (1998) found even higher rates of introduction in the San Francisco Bay area. International efforts to prevent ballast water-related introductions, through the International Maritime Organization and others, are having some impact, but this remains a serious focus of concern. Plants can be aquatic invasive species as well: witness the water hyacinth, *Eichhornia crassipes*, which spreads over lake surfaces, choking local vegetation and reducing oxygen availability; it is a major hindrance in Africa in particular, though it does appear to have some natural limits to its cyclical spread (Albright et al. 2004).[21]

Climate change will further exacerbate the problem of aquatic invasive species as temperatures increase and the range of invasive species, such as zebra mussels and Asian carp, are extended. Another example is the European green crab, harmful to native species in the US and parts of Africa and Australia; it has been slow to spread northward because of colder water temperatures, but this is slowly changing with global warming (Floyd and Williams 2004). In some cases, climate change will join invasive species as major stressors on struggling native species populations, further reinforcing the spread of aquatic IAS through common vectors such as ship traffic and tourism.[22] For example, melting sea ice opens new vectors for bioinvasion in the Arctic (and indeed, melting ice itself can release previously unknown pathogens, locked into ice formations for thousands of years, into the Arctic environment). Increasing levels of photo-degraded microplastic can also serve as a vector for microbial communities (Zettler et al. 2013).

While the impact of IAS on biodiversity and ecosystems is well documented (e.g. Charles 2007), resultant impacts on human health are an important area for further research (see Pysek and Richardson 2010). Deleterious waterborne pathogens, such as those that cause cholera, are often classified as invasive species (see the chapter on infectious diseases in this volume). Other aquatic invasive species, such as the zebra mussel described above, not only disrupt local food security networks but can also act as causative agents of harmful algal blooms (Hallegraeff 1998; Coetzee and Hill 2012), threaten the availability of clean water supplies, and pose other significant health threats (McNeely 2001). Invasive bivalves can clog machinery vital for the operation of energy plants and well as fishing boat equipment. Water hyacinth (*Eichhornia crossipes*) can make small-scale freshwater fishing next to impossible, directly lowering food security and nutrition levels for local communities. Moreover, its introduction in Lake Victoria has also been found to contribute to the spread of waterborne diseases (Pejchar and Mooney 2009 and reference therein). Efforts to eradicate aquatic IAS can also carry health hazards if they employ lampricides and other agents that can contaminate water supplies (though sea lamprey eradication efforts in North America

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[20] See http://www.ec.gc.ca/inre-nwri/default.asp?lang=En&n=832CDC7B&xsl=articlesservices,viewfull&po=0E367B85. The relationship with climate change is also complex: warmer temperatures will extend the range northward; and zebra mussels release carbon dioxide into the aquatic environment.

[21] For a recent discussion on the impact of water hyacinth in South Africa, see for example Coetzee et al. (2014), and for a discussion on the role of eutrophication in its biological control, see Coetzee and Hill (2012).

[22] As a major EPA report suggested in 2008, in order "to effectively prevent invasions that might result from or be influenced by climate-change factors, a first step should be to identify specific aquatic invasive species threats, including new pathways and vectors, which may result as environmental conditions such as water and air temperatures, precipitation patterns, or sea levels change" (EPA 2008:61).

have been relatively successful with limited controversy). Moreover, the losses posed by IAS can be harmful to the well-being of communities whose sense of place may be disrupted in areas affected by IAS (McNeely 2001). It is vital that efforts are made to avoid introductions whenever possible, and to employ the precautionary principle when contemplating future purposeful introductions.

6. Ways forward and additional considerations

It is clear that healthy freshwater systems are central to the protection of biodiversity as well as to the promotion of human health and well-being. It is also evident that there are severe threats to water security and ecosystem health; and that waterborne diseases, the loss of aquatic biodiversity, and the disruption of complex ecosystems represent major public health challenges. A concerted effort to conserve freshwater resources is necessary on a global scale. While this chapter has focused primarily on freshwater systems, it is equally apparent that oceans and related biodiversity face threats from pollution, climate change, coral bleaching, acidification and other anthropocentric factors, and that an international effort to conserve them is vital (Stoett 2012:107–28). These impacts extend to human health, an area that clearly merits greater scientific attention. The European Marine Board recently published a position paper to this effect on "Linking oceans and human health: a strategic research priority for Europe",[23] which highlights the substantive and complex interactions between the marine environment and human health and well-being (Flemming et al. 2014).

Moreover, we are only beginning to understand the impact climate change will have on aquatic ecosystems and human health (see the chapter on climate change in this volume). In a recent background report written for the European Environmental Agency, the European Topic Centre on Water concluded that climate change would have multiple impacts, including:

- physical changes such as increased water temperature, reduced river and lake ice cover, more stable vertical stratification and less mixing of water of deep-water lakes, and changes in water discharge, affecting water level and retention time;

- chemical changes, such as increased nutrient concentrations and water colour, and decreased oxygen content (DOC);

- biological changes, including northwards migration of species and alteration of habitats, affecting the structure and functioning of freshwater ecosystems (European Topic Centre on Water 2010: 5)

It is clear that all of these changes will affect human security in terms of our physical and emotional connections with water, and the ecosystem services provided by aquatic ecosystems. We will need to adapt to them, but we can also be more proactive by promoting biodiversity conservation and restoration.

Water resources will remain central to human and community development. The biodiversity–health nexus is readily apparent in this context. However, much remains to be done regarding the management and equitable use of water resources, including preventive measures to avoid increased waterborne disease and aquatic invasive species. The WHO Guidelines for drinking-water quality establish a basis for the pursuit of a healthier human species (WHO 2010b). Recognition of the key role played by biodiversity in freshwater systems is an important element in that pursuit as well. Recent laboratory research suggests that there is a positive correlation between species diversity and the ability of water systems to filter nutrient pollutants such as nitrate (Cardinale 2011) as well as pharmaceuticals (Binellia et al. 2014). More than ever, the biodiversity and global public health communities, including key decision-makers and private sector actors, need to work together towards a healthier blue planet.

[23] http://www.marineboard.eu/images/publications/Oceans%20and%20Human%20Health-214.pdf

Some meaningful (but by no means exhaustive) considerations include the following:

We must take stock of our ecological capital in ways that will benefit human health. Water and other ecosystem services must be linked to broader frameworks that consider public health concerns within broader ecosystem restoration and conservation frameworks, such as the ecosystem or One Health approach. Knowledge exchange and cross-sectoral collaboration will be critical to share and mutually learn from experiences.

The Ramsar Convention on Wetlands is a critical instrument in the pursuit of water security. As of early 2015, 2186 sites, encompassing 208 449 277 hectares of surface area, have been classified as wetlands of international importance. The Ramsar Convention, in force since 1975, advocates the "wise use" of wetlands, defined as "the maintenance of their ecological character, achieved through the implementation of ecosystem approaches, within the context of sustainable development".[24]

The pollution of freshwater lakes and the oceans must be halted to protect their indigenous biodiversity. Micro-plastics are a particularly pernicious pollutant, harming wildlife as they enter the food chain and providing vectors for invasive species. International efforts to stop the pollution and clean oceans, lakes and rivers will be pivotal in the near future if we are to avoid the further development of what scientists have referred to as the "plastisphere" (Zettler et al. 2013).

The impact of climate change on water biodiversity must be closely monitored and efforts to reduce greenhouse gas emissions should receive extra attention, given the centrality of water biodiversity to human health. This calls for more scientific research, including taxonomic studies focusing on the use of bioindicators to assess ecosystem condition (Buss et al. 2015), and more studies linking the impacts of biodiversity loss on human health, as well as serious regulatory policy development.

The impact of water quality and quantity on human health is one of several critical areas described in this volume, which underscores the need to develop robust, cross-sectoral integrated approaches, such as the ecosystem or One Health approach to water management and to the broader management of ecosystems (including agroecosystems). Researchers, policy-makers and those that manage natural resources must also work to compile and share regionally specific data on how functional metrics vary over space and time (Palmer and Febria 2012) and produce a more composite idea of related water footprints (see Box 2 on cotton production). Applying a holistic framework to water and food security, and other critical themes at the biodiversity–health nexus, makes it possible to manage ecosystems (including water and agroecosystems) that are more resilient, sustainable and productive, that remain productive in the long term, and that yield a wide range of ecosystem services. A socioecological perspective will further ensure that vulnerable populations most affected by the global disease burden and ecosystem degradation are also considered. These considerations will be imperative as we move from the MDGs toward the Sustainable Development Goals and the post-2015 Development Agenda.

[24] http://www.ramsar.org/cda/en/ramsar-home/main/ramsar/1_4000_0

4. Biodiversity, air quality and human health

1. Introduction

Air pollution is a significant problem in cities across the world. It affects human health and well-being, ecosystem health, crops, climate, visibility and human-made materials. Health effects related to air pollution include its impact on the pulmonary, cardiac, vascular and neurological systems (Section 2). Trees affect air quality through a number of means (Section 3) and can be used to improve air quality (Section 4). However, air pollution also affects tree health and plant diversity (Section 5). Bioindicators can be useful for monitoring air quality and indicating environmental health (Section 6). Understanding the impacts of vegetation biodiversity on air quality and air quality on vegetation biodiversity is essential to sustaining healthy and diverse ecosystems, and for improving air quality and consequently human health and well-being.

2. Air pollution and its effects on human health

Air pollution can significantly affect human and ecosystem health (US EPA 2010). Recent research indicates that global deaths directly or indirectly attributable to outdoor air pollution reached 7 million in 2012 (WHO 2014[1]). This was equivalent to 1 in every 8 deaths globally, making air pollution the most important environmental health risk worldwide (WHO 2014a). Other diseases affected by air pollution include cardiovascular disease, immune disorders, various cancers, and disorders of the eye, ear, nose and throat such as cataract and sinusitis. Epidemiological evidence suggests that prenatal exposure to certain forms of air pollution can harm the child, affecting birth outcomes and infant mortality. Childhood exposure to some pollutants also appears to increase the risk of developing health problems in later life, affecting the development of lung function and increasing the risk for development of chronic obstructive pulmonary disease (COPD) and asthma.

Several respiratory illnesses caused or otherwise affected by air pollution are on the rise. These include bronchial asthma, which affects between 100 and 150 million people worldwide, with another 65 million affected by some form of COPD. Other human health problems from air pollution include: aggravation of respiratory and cardiovascular disease, decreased lung function, increased frequency and severity of respiratory symptoms (e.g. difficulty in breathing and coughing, increased susceptibility to respiratory

[1] World Health Organization, 2015. Health and the Environment: Addressing the health impact of air pollution. Sixty-eighth World Health Assembly, Agenda item 14.6. A68/A/CONF./2 Rev.1 26 May 2015. http://apps.who.int/gb/ebwha/pdf_files/WHA68/A68_ACONF2Rev1-en.pdf (last accessed June 2015)

infections), effects on the nervous system (e.g. impacts on learning, memory and behaviour), cancer and premature death (e.g. Pope et al. 2002). People with pre-existing conditions (e.g. heart disease, asthma, emphysema), diabetes, and older adults and children are at greater risk for air pollution-related health effects. In the United States (US), approximately 130 000 particulate matter $(PM)_{2.5}$-related deaths and 4700 ozone (O_3)-related deaths in 2005 were attributed to air pollution (Fann et al. 2012).

Air pollution comes from numerous sources. Major causes of gaseous and particulate outdoor air pollution with a direct impact on public health include the combustion of fossil fuels associated with transport, heating and electricity generation, and industrial processes such as smelting, concrete manufacture and oil refining. Other important sources include ecosystem degradation (including deforestation and wetland drainage) and desertification.

Plants provide an important ecosystem service through the regulation of air quality. Although the effects of plants on air quality are generally positive, they can also to some degree be negative (as discussed in section 3 below). Likewise, air quality can have both positive and negative impacts on plant populations. These various impacts are partially dependent upon the diversity of the plant species, vegetation assemblages and size classes. This chapter explores the role of biodiversity in regulating air quality in positive and negative terms, including a discussion of current knowledge gaps and recommendations.

Air pollution also affects the environment. Ozone and other pollutants can damage plants and trees, and pollution can lead to acid rain. Acid rain can harm vegetation by damaging tree leaves and stressing trees through changing the chemical and physical composition of the soil. Particles in the atmosphere can also reduce visibility. The typical visual range in the eastern US parks is 15–25 miles, approximately one third of what it would be without human-induced air pollution. In western USA, the visual range has decreased from 140 miles to 35–90 miles (US EPA 2014). Air pollution also affects the earth's climate by either absorbing or reflecting energy, which can lead to climate warming or cooling, respectively.

Indoor air pollution is primarily associated with particulates from combustion of solid fuel (wood, coal, turf, dung, crop waste, etc.) and oil for heating and cooking, and gases from all fuels (including natural gas) in buildings with inadequate ventilation or smoke removal. The World Health Organization (WHO) reports that over 4 million people die prematurely from illness attributable to household air pollution from cooking with solid fuels. More than 50% of premature deaths among children under 5 years of age are due to pneumonia caused by particulate matter (soot) inhaled from household air pollution. It is estimated that 3.8 million premature deaths annually from noncommunicable diseases (including stroke, ischaemic heart disease, lung cancer and COPD) are attributable to exposure to household air pollution (WHO 2014b).

Some pollutants, both gaseous and particulate, are directly emitted into the atmosphere and include sulfur dioxide (SO_2), nitrogen oxides (NO_x), carbon monoxide (CO), particulate matter (PM) and volatile organic compounds (VOC). Other pollutants are not directly emitted; rather, they are formed through chemical reactions. For example, ground-level O_3 is often formed when emissions of NO_x and VOCs react in the presence of sunlight. Some particles are also formed from other directly emitted pollutants.

3. Impacts of vegetation on air quality

There are three main ways in which plants affect local air pollution levels: via effects on local microclimate and energy use, removal of air pollution, and emission of chemicals. Each of these are described below.

1) Effects of plants on local microclimate and energy use

Increased air temperature can lead to increased energy demand (and related emissions) in the summer (e.g. to cool buildings), increased air pollution and heat-related illness. Vegetation, particularly trees, alters microclimates and cools the air through evaporation from tree transpiration, blocking winds and shading various surfaces. Local environmental influences on air temperature include the amount of tree cover, amount of impervious surfaces in the area, time of day, thermal stability, antecedent moisture condition and topography (Heisler et al. 2007). Vegetated areas can cool the surroundings by several degrees Celsius, with higher tree and shrub cover resulting in cooler air temperatures (Chang et al. 2007). Trees can also have a significant impact on wind speed, with measured reductions in wind speed in high-canopy residential areas (77% tree cover) of the order of 65–75% (Heisler 1990).

2Temperature reduction and changes in wind speed in urban areas can have significant effects on air pollution. Lower air temperatures can lead to lower emission of pollutants, as pollutant emissions are often related to air temperatures (e.g. evaporation of VOCs). In addition, reduced urban air temperatures and shading of buildings can reduce the amount of energy used to cool buildings in the summer time, as buildings are cooler and air conditioning is used less. However, shading of buildings in winter can lead to increased building energy use (e.g. Heisler 1986).[2] In addition to temperature effects, trees affect wind speed and mixing of pollutants in the atmosphere, which in turn affect local pollutant concentrations. These changes in wind speed can lead to both positive and negative effects related to air pollution. On the positive side, reduced wind speed due to shelter from trees and forests will tend to reduce winter-time heating energy demand by tending to reduce cold air infiltration into buildings. On the negative side, reductions in wind speed can reduce the dispersion of pollutants, which will tend to increase local pollutant concentrations. In addition, with lower wind speeds, the height of the atmosphere within which the pollution mixes can be reduced. This reduction in the "mixing height" tends to increase pollutant concentrations, as the same amount of pollution is now mixed within a smaller volume of air.

2) Removal of air pollutants

Trees remove gaseous air pollution primarily by uptake through the leaves, though some gases are removed by the plant surface. For O_3, SO_2 and NO_2, most of the pollution is removed via leaf stomata.[3] Healthy trees in cities can remove significant amounts of air pollution. The amount of pollution removed is directly related to the amount of air pollution in the atmosphere (if there is no air pollution, the trees will remove no air pollution). Areas with a high proportion of vegetation cover will remove more pollution and have the potential to effect greater reductions in air pollution concentrations in and around these areas. However, pollution concentration can be increased under certain conditions (see Section 4). Pollution removal rates by vegetation differ among regions according to the amount of vegetative cover and leaf area, the amount of air pollution, length of in-leaf season, precipitation and other meteorological variables.

There are numerous studies that link air quality to the effects on human health. With relation to trees, most studies have investigated the

[2] This altered energy use consequently leads to altered pollutant emissions from power plants used to produce the energy used to cool or heat buildings. Air temperatures reduced by trees can not only lead to reduced emission of air pollutants from numerous sources (e.g. cars, power plants), but can also lead to reduced formation of O_3 ,as O_3 formation tends to increase with increasing air temperatures.

[3] Trees also directly affect particulate matter in the atmosphere by intercepting particles, emitting particles (e.g. pollen) and resuspending particles captured on the plant surface. Some particles can be absorbed into the tree, though most intercepted particles are retained on the plant surface. Many of the particles that are intercepted are eventually resuspended back to the atmosphere, washed off by rain, or dropped to the ground with leaf and twig fall. During dry periods, particles are constantly intercepted and resuspended, in part, dependent upon wind speed. During precipitation, particles can be washed off and either dissolved or transferred to the soil. Consequently, vegetation is only a temporary retention site for many atmospheric particles, though the removal of gaseous pollutants is more permanent as the gases are often absorbed and transformed within the leaf interior.

magnitude of the effect of trees on pollution removal or concentrations, while only a limited number of studies have looked at the estimated health effects of pollution removal by trees. In the United Kingdom, woodlands are estimated to save between 5 and 7 deaths, and between 4 and 6 hospital admissions per year due to reduced pollution by SO_2 and particulate matter less than 10 microns (PM_{10}) (Powe and Willis 2004). Modelling for London estimates that 25% tree cover removes 90.4 metric tons of PM_{10} pollution per year, which equates to a reduction of 2 deaths and 2 hospital stays per year (Tiwary et al. 2009). Nowak et al. (2013) reported that the total amount of particulate matter less than 2.5 microns ($PM_{2.5}$) removed annually by trees in 10 US cities in 2010 varied from 4.7 t in Syracuse to 64.5 t in Atlanta. Estimates of the annual monetary value of human health effects associated with $PM_{2.5}$ removal in these same cities (e.g. changes in mortality, hospital admissions, respiratory symptoms) ranged from $1.1 million in Syracuse to $60.1 million in New York City. Mortality avoided was typically around 1 person per year per city, but was as high as 7.6 people per year in New York City.

Trees and forests in the conterminous US removed 22.4 million t of air pollution in 2010 (range: 11.1–31.0 million t), with human health effects valued at US$ 8.5 billion (range: $2.2–15.6 billion). Most of the pollution removal occurred in rural areas, while most of the health impacts and values were within urban areas. Health impacts included the avoidance of more than 850 incidences of human mortality. Other substantial health benefits included the reduction of more than 670 000 incidences of acute respiratory symptoms (range: 221 000–1 035 000), 430 000 incidences of asthma exacerbation (range: 198 000–688 000) and 200 000 days of school loss (range: 78 000–266 000) (Nowak et al. 2014).

Though the amount of air pollution removed by trees may be substantial, the per cent air quality improvement in an area will depend upon on the amount of vegetation and meteorological conditions. Air quality improvement by trees in cities during daytime of the in-leaf season averages around 0.51% for particulate matter, 0.45% for O_3, 0.44% for SO_2, 0.33% for NO_2, and 0.002% for CO. However, in areas with 100% tree cover (i.e. contiguous forest stands), air pollution improvement is on an average around four times higher than city averages, with short-term improvements in air quality (1 hour) as high as 16% for O_3 and SO_2, 13% for particulate matter, 8% for NO_2, and 0.05% for CO (Nowak et al. 2006).

3) Emission of chemicals

Vegetation, including trees, can emit various chemicals that can contribute to air pollution. Because some vegetation, particularly urban vegetation, often requires relatively large inputs of energy for maintenance activities, the resulting emissions need to be considered. The use and combustion of fossil fuels to power this equipment leads to the emission of chemicals such as VOCs, CO, NO_2 and SO_2, and particulate matter (US EPA 1991).

Plants also emit VOCs (e.g. isoprene, monoterpenes) (Geron et al. 1994; Guenther 2002; Nowak et al. 2002; Lerdau and Slobodkin 2002). These compounds are natural chemicals that make up essential oils, resins and other plant products, and may be useful in attracting pollinators or repelling predators. Complete oxidation of VOCs ultimately produces carbon dioxide (CO_2), but CO is an intermediate compound in this process. Oxidation of VOCs is an important component of the global CO budget (Tingey et al. 1991); CO also can be released from chlorophyll degradation (Smith 1990). VOCs emitted by trees can also contribute to the formation of O_3. Because VOC emissions are temperature dependent and trees generally lower air temperatures, increased tree cover can lower overall VOC emissions and, consequently, O_3 levels in urban areas (e.g. Cardelino and Chameides 1990). Ozone inside leaves can also be reduced due to the reactivity with biogenic compounds (Calfapietra et al. 2009).

Trees generally are not considered as a source of atmospheric NO_x, though plants, particularly agricultural crops, are known to emit ammonia.

Emissions occur primarily under conditions of excess nitrogen (e.g. after fertilization) and during the reproductive growth phase (Schjoerring 1991). They can also make minor contributions to SO_2 concentration by emitting sulfur compounds such as hydrogen sulfide (H_2S) and SO_2 (Garsed 1985; Rennenberg 1991). H_2S, the predominant sulfur compound emitted, is oxidized in the atmosphere to SO_2. Higher rates of sulfur emission from plants are observed in the presence of excess atmospheric or soil sulfur. However, sulfur compounds also can be emitted with a moderate sulfur supply (Rennenberg 1991). In urban areas, trees can additionally contribute to particle concentrations by releasing pollen and emitting volatile organic and sulfur compounds that serve as precursors to particle formation. From a health perspective, pollen particles can lead to allergic reactions (e.g. Cariñanosa et al. 2014).

3.1 Overall effect of vegetation on air pollution

There are many factors that determine the ultimate effect of vegetation on pollution. Many plant effects are positive in terms of reducing pollution concentrations. For example, trees can reduce temperatures and thereby reduce emissions from various sources, and they can directly remove pollution from the air. However, the alteration of wind patterns and speeds can affect pollution concentrations in both positive and negative ways. In addition, plant compound emissions and emissions from vegetation maintenance can contribute to air pollution. Various studies on O_3, a chemical that is not directly emitted but rather formed through chemical reactions, have helped to illustrate the cumulative and interactive effects of trees.

One model simulation illustrated that a 20% loss in forest cover in the Atlanta area due to urbanization led to a 14% increase in O_3 concentrations for a day (Cardelino and Chameides 1990). Although there were fewer trees to emit VOCs, an increase in Atlanta's air temperatures due to the increased urban heat island, which occurred concomitantly with tree loss, increased VOC emissions from the remaining trees and other sources (e.g. automobiles), and altered O_3 chemistry such that concentrations of O_3 increased. Another model simulation of California's South Coast Air Basin suggests that the air quality impacts of increased urban tree cover may be locally positive or negative with respect to O_3. However, the net basinwide effect of increased urban vegetation is a decrease in O_3 concentrations if the additional trees are low VOC emitters (Taha 1996).

Modelling the effects of increased urban tree cover on O_3 concentrations from Washington, DC to central Massachusetts revealed that urban trees generally reduce O_3 concentrations in cities, but tend to slightly increase average O_3 concentrations regionally (Nowak et al. 2000). Modelling of the New York City metropolitan area also revealed that increasing tree cover by 10% within urban areas reduced maximum O_3 levels by about 4 ppb, which was about 37% of the amount needed for attainment (Luley and Bond 2002).

4. The role of plant biodiversity in regulating air quality

The impacts of vegetation on air quality depend in part on species and other aspects of plant biodiversity. Plant biodiversity in an area is influenced by a mix of natural and anthropogenic factors that interact to produce the vegetation structure. Natural influences include native vegetation types and abundance, natural biotic interactions (e.g. seed dispersers, pollinators, plant consumers), climate factors (e.g. temperature, precipitation), topographic moisture regimes, and soil types. Superimposed on these natural systems in varying degrees is an anthropogenic system that includes people, buildings, roads, energy use and management decisions. The management decisions made by multiple disciplines within an urban system can both directly (e.g. tree planting, removal, species introduction, mowing, paving, watering, use of herbicides and fertilizers) and indirectly (e.g. policies and funding related to vegetation and development) affect vegetation structure and biodiversity. In addition, the anthropogenic system alters the environment (e.g. changes in air temperature and solar radiation, air pollution, soil compaction) and can induce changes in vegetation structure (Nowak 2010).

Much is generally known about plant distribution globally, but less is known about factors that affect the distribution of plant diversity and human influences on plant biodiversity (Kreft and Jetz 2007). Variations in urban tree cover across regions and within cities give an indication of the types of factors that can affect urban tree structure and consequently biodiversity, with resulting impacts on human health. One of the dominant factors affecting tree cover in cities is the natural characteristics of the surrounding region. For example, in forested areas of the US, urban tree cover averages 34%. Cities within grassland areas average 18% tree cover, while cities in desert regions average only 9% tree cover (Nowak et al. 2001). Cities in areas conducive to tree growth naturally tend to have more tree cover, as non-managed spaces tend to naturally regenerate with trees. In forested areas, tree cover is often specifically excluded by design or management activities (e.g. impervious surfaces, mowing). In the US, while the per cent tree cover nationally in urban (35.0%) and rural areas (34.1%) are comparable, urbanization tends to decrease overall tree cover in naturally forested areas, but increase tree cover in grassland and desert regions (Nowak and Greenfield 2012).

In urban areas, land use, population density, management intensity, human preferences and socioeconomic factors can affect the amount of tree cover and plant diversity (Nowak et al. 1996; Hope et al. 2003; Kunzig et al. 2005). These factors are often interrelated and create a mosaic of tree cover and species across the city landscape. Land use is a dominant factor affecting tree cover (Table 1). However, land use can also affect species composition, as non-managed lands (e.g. vacant) tend to be dominated by natural regeneration of native and exotic species. Within areas of managed land use, the species composition tends to be dictated by a combination of human preferences for certain species (tree planting) and how much land is allowed to naturally regenerate (Nowak 2010).

Tree diversity, represented by the common biodiversity metrics of species richness (number of species) and the Shannon–Wiener diversity index (Barbour et al. 1980), varies among and within cities and through time. Based on field sampling of various cities in North America (Nowak et al. 2008; Nowak 2010), species richness varied from 37 species in Calgary, Alberta, Canada, to 109 species in Oakville, Ontario, Canada (Figure 1). Species diversity varied from 1.6 in Calgary to 3.8 in Washington, DC (Figure 2). The species richness in all cities is greater than the average species richness in eastern US forests by county (26.3) (Iverson and Prasad 2001). Species diversity

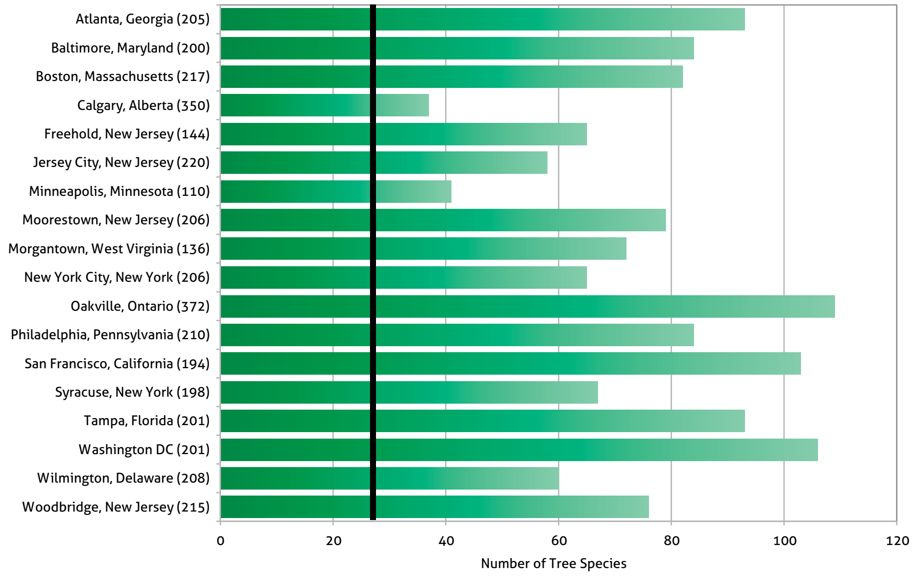
Table 1: Mean per cent tree cover and standard error (SE) for US cities with different potential natural vegetation types (forest, grassland, desert) by land use (from Nowak et al. 1996)

	Forest		Grassland		Desert	
Land use	Mean	SE	Mean	SE	Mean	SE
Park	47.6	5.9	27.4	2.1	11.3	3.5
Vacant/wildland	44.5	7.4	11.0	2.5	0.8	1.9
Residential	31.4	2.4	18.7	1.5	17.2	3.5
Institutional	19.9	1.9	9.1	1.2	6.7	2.0
Other[1]	7.7	1.2	7.1	1.9	3.0	1.3
Commercial/industrial	7.2	1.0	4.8	0.6	7.6	1.8

[1]Includes agriculture, orchards, transportation (e.g., freeways, airports, shipyards), and miscellaneous.

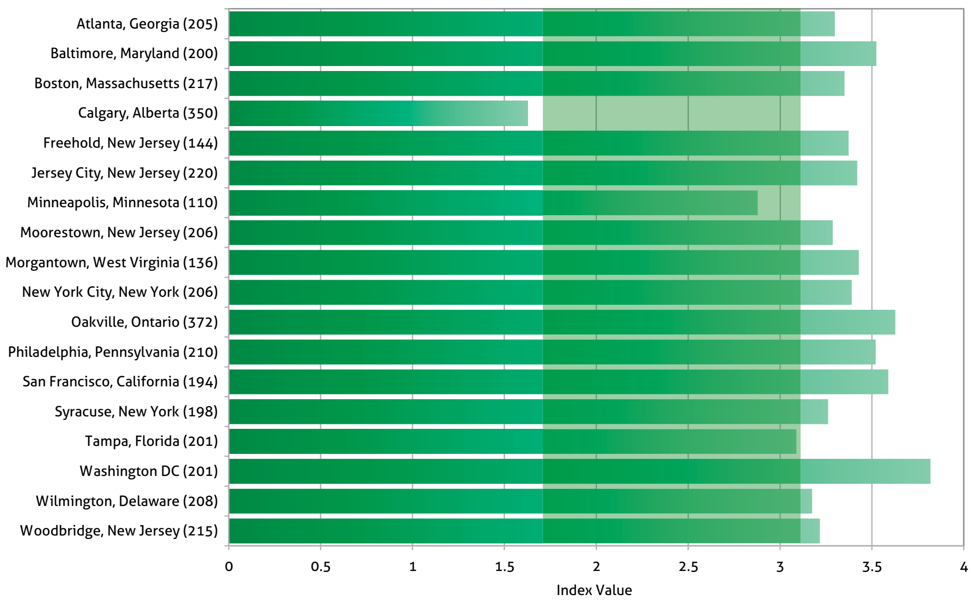
in these urban areas is also typically greater than found in eastern US forests (Barbour et al. 1980). Tree species diversity and richness is enhanced in urban areas compared with surrounding landscapes and/or typical forest stands, as native species richness is supplemented with species introduced by urban inhabitants or processes. People often plant trees in urban areas to improve aesthetics and/or the physical or social environment. Some non-native species can be introduced via transportation corridors or escape from cultivation (e.g. Muehlenbach 1969; Haigh 1980).

FIGURE 1: Species richness and values for tree populations in various cities. Numbers in parentheses are sample size based on 0.04 hectare plots. (A) Dark line indicates average species richness in eastern US forests by county (26.3).



Source: Nowak 2010

(B) Shannon–Wiener Diversity Index values. Shaded area indicates typical range of diversity values for forests in the eastern US (1.7–3.1).



Source: Nowak 2010

One of the most important vegetation attributes in relation to air quality is the amount of leaf area. Leaf area varies by plant form, with leaf area indices (m^2 leaf surface area per m^2 ground) of agricultural areas typically around 3–5 and leaf area indices of forests typically between 5 and 11 (Barbour et al. 1980). Thus, the magnitude and distribution of vegetation types (e.g. grasses, shrubs, trees) affect air quality. In general, plant types with more leaf area or leaf biomass have a greater impact, either positive or negative, on air quality.[4]

The second most important attribute related to air quality is vegetation configuration or design. Though reduction in wind speeds can increase local pollution concentrations due to reduced dispersion of pollutants and mixing height of the atmosphere, altering of wind patterns can also have a potential positive effect. Tree canopies can potentially prevent pollution in the upper atmosphere from reaching ground-level air space. Measured differences in O_3 concentration between above- and below-forest canopies in California's San Bernardino mountains have exceeded 50 ppb (40% improvement) (Byternowicz et al. 1999). Under normal daytime conditions, atmospheric turbulence mixes the atmosphere such that pollutant concentrations are relatively consistent with height. Forest canopies can limit the mixing of upper air with ground-level air, leading to below-canopy air quality improvements. However, where there are numerous pollutant sources below the canopy (e.g. automobiles), the forest canopy could increase concentrations by minimizing the dispersion of the pollutants away at ground level. This effect could be particularly important in heavily treed areas near roadways (Gromke and Ruck 2009; Wania et al. 2012; Salmond et al. 2013; Vos et al. 2013). However, standing in the interior of a forest stand can offer cleaner air if there are no local ground sources of emissions (e.g. from automobiles). Various studies have illustrated reduced pollutant concentrations in the interior of forest stands compared to the outside of the forest stands (e.g. Dasch 1987; Cavanagh et al. 2009).

The biodiversity of plant types within an area affects the total amount of leaf area and the vegetation design. Following biodiversity related to plant form, species diversity also affects air quality, as different species have different effects based on species characteristics. In general, species with larger growth forms and size at maturity have greater impacts, either positive or negative, on air quality. The following are the types of air quality impacts that can be affected by species and therefore species diversity:

Pollution removal: in addition to total leaf area of a species, species characteristics that affect pollution removal are tree transpiration and leaf characteristics. Removal of gaseous pollutants is affected by tree transpiration rates (gas exchange rates). As actual transpiration rates are highly variable, depending upon site or species characteristics, limited data exist on transpiration rates for various species under comparable conditions. However, relative transpiration factors for various species can be gauged from estimated monthly water use (Costello and Jones 1994). Particulate matter removal rates vary depending upon leaf surface characteristics. Species with dense and fine textured crowns and complex, small and rough leaves would capture and retain more particles than open and coarse crowns, and simple, large, smooth leaves (Little 1997; Smith 1990). Species ranking of trees in relation to pollution removal are estimated in i-Tree Species (www.itreetools.org). In addition, evergreen trees provide for year-round removal of particles.

VOC emissions: emission rates of VOCs vary by species (e.g. Geron et al. 1994; Nowak et al. 2002). Nine tree genera that have the highest standardized isoprene emission rate, and therefore the greatest relative effect on increasing O_3, are beefwood (*Casuarina* spp.), *Eucalyptus* spp., sweetgum (*Liquidambar* spp.), black gum (*Nyssa* spp.), sycamore (*Platanus* spp.), poplar (*Populus*

[4] Within forests, leaf area also varies with tree age/size, with large healthy trees greater than 30 inches in stem diameter in Chicago having approximately 60–70 times more leaf area than small healthy trees less than 3 inches in diameter (Nowak 1994).

spp.), oak (*Quercus* spp.), black locust (*Robinia* spp.) and willow (*Salix* spp.). However, due to the high degree of uncertainty in atmospheric modelling, results are currently inconclusive as to whether these genera contribute to an overall net formation of O_3 in cities (i.e. O_3 formation from VOC emissions is greater than O_3 removal).

Pollen: not only do pollen emissions and phenology of emissions vary by species, but pollen allergenicity also varies by species. Examples of some of the most allergenic species are *Acer negundo* (male), *Ambrosia* spp., *Cupressus* spp., *Daucus* spp., *Holcus* spp., *Juniperus* spp. (male), *Lolium* spp., *Mangifera indica*, *Planera aquatica*, *Ricinus communis*, *Salix alba* (male), *Schinus* spp. (male) and *Zelkova* spp. (Ogren 2000).

Air temperature reduction: similar to gaseous air pollution removal, species effects on air temperatures vary with leaf area and transpiration rates. Leaf area affects tree shading of ground surfaces and also overall transpiration. Transpiration from the leaves helps to provide evaporative cooling. Both the shade and evaporative cooling, along with effects on wind speed, affect local air temperature and therefore pollutant emission and formation.

Building energy conservation: although the effects of trees on building energy use is dependent upon a tree's position (distance and direction) relative to the building, tree size also plays a role on building energy effects (McPherson and Simpson 2000). Changes in building energy use affect pollutant emission from power plants.

Maintenance needs: like building energy conversation, species maintenance needs have a secondary effect on air quality. Plant species with greater maintenance needs typically require more human interventions (planting, pruning, removal) that utilize fossil fuel-based equipment (e.g. cars, lawn mowers, chain saws). The more fossil fuel-based equipment is used, the more pollutant emissions are produced. Plant attributes that affect maintenance needs include not only plant adaptation to site conditions but also plant life span (e.g. shorter lived species require more frequent planting and removal).

Pollution sensitivity: sensitivity to various pollutants vary by plant species. For example, *Populus tremuloides* and *Poa annua* are sensitive to O_3, but *Tilia americana* and *Dactylis glomerata* are resistant. Pollutant sensitivity to various species is given in Smith and Levenson (1980).

5. Impacts of air quality on plant communities

Air pollution can affect tree health. Some pollutants under high concentrations can damage leaves (e.g. SO_2, NO_2, O_3), particularly of pollutant-sensitive species. For NO_2, visible leaf injury would be expected at concentrations around 1.6–2.6 ppm for 48 hours, 0 ppm for 1 hour, or a concentration of 1 ppm for as many as 100 hours (Natl. Acad. of Sci. 1977a). Concentrations that would induce foliage symptoms would be expected only in the vicinity of an excessive industrial source (Smith 1990).

Eastern deciduous species are injured by exposure to O_3 at 0.20–0.30 ppm for 2–4 hours (Natl. Acad. of Sci. 1977b). The threshold for visible injury of eastern white pine is approximately 0.15 ppm for 5 hours (Costonis 1976). Sorption of O_3 by white birch seedlings shows a linear increase up to 0.8 ppm; for red maple seedlings the increase is up to 0.5 ppm (Townsend 1974). Severe O_3 levels in urban areas can exceed 0.3 ppm (Off. Technol. Assess. 1989). Injury effects can include altered photosynthesis, respiration, growth and stomatal function (Lefohn et al. 1988; Shafer and Heagle 1989; Smith 1990).

Toxic effects of SO_2 may be due to its acidifying influence and/or the sulfite (SO_3^{2-}) and sulfate (SO_4^{2-}) ions that are toxic to a variety of biochemical processes (Smith 1990). Stomata may exhibit increases in either stomatal opening or stomatal closure when exposed to SO_2 (Smith 1984; Black 1985). Acute SO_2 injury to native vegetation does not occur below 0.70 ppm for 1 hour or 0.18 ppm for 8 hours (Linzon 1978). A concentration of 0.25 ppm for several hours may injure some species

(Smith 1990). Indirect anthropogenic effects can alter species composition. For example, in a natural park in Tokyo, Japanese red pine (*Pinus densiflora*) was dying and being successionally replaced with broad-leaved evergreen species (Numata 1977). This shift in species composition has been attributed to SO_2 air pollution, with the broad-leaved species being more resistant to air pollution.

Particulate trace metals can be toxic to plant leaves. The accumulation of particles on leaves also can reduce photosynthesis by reducing the amount of light reaching the leaf. Damage to plant leaves can also occur from acid rain (pH <3.0). Acid rain and air pollution (NAPAP 1991) can be a source of the essential plant nutrients of sulfur and nitrogen, but also can reduce soil nutrient availability through leaching or toxic soil reactions. Particles can also affect tree pest/disease populations. Given the pollution concentration in most cities, these pollutants would not be expected to cause visible leaf injury, but could in cities or areas with high pollutant concentrations.

6. Bioindicators

A bioindicator is a quality of an organism, population, community or ecosystem used for indicating the health or status of the surrounding environment. Bioindicators, especially lichens and bryophytes, are widely used for monitoring air quality. The benefits of direct measurements of air quality include long-term integration of pollution levels over time and lower operational costs (often by orders of magnitude per study site). Biodiversity metrics, such as the number of sensitive species, relative abundance of functional groups, or genotypic frequencies, for example, are successfully employed for air quality biomonitoring in many nations (Markert et al. 1996; Aničić et al. 2009; Cao et al. 2009). Measuring pollutant concentrations in lichen and bryophyte tissues is another means of air quality mapping (Augusto et al. 2007; Augusto et al. 2010; Liu et al. 2011; Root et al. 2013). Most studies focus on environmental health (i.e. evaluating pollutant-mediated harms to the natural environment) to guide land management and air quality regulation (Hawksworth and Rose 1970; Cape et al. 2009; Geiser et al. 2010). Health and bioindicator experts often suggest utilizing bioindicators in public health assessments to overcome the lack of systematic air quality measurements from instrumented monitoring networks and for detecting chronic low levels of pollution below the detection limits of monitoring instruments (Brauer 2010; Augusto et al. 2012). Tissue-based bioindicators enable high spatial resolution mapping of toxic pollutants that are not frequently measured by instrumented networks. Nonetheless, it is rare for research to actually integrate bioindicator and public health data.

UNITED NATIONS PHOTO / FLICKR

Taking cues from the environment to assess air quality is a relatively old science. Lichens were first described as "health meters for the air" in 1866, when a Finnish botanist noted that certain species were restricted to a large city park in Paris (Nylander 1866). While many organisms exhibit a measurable response to pollution, lichen and bryophytes (i.e. mosses and liverworts) are the most widely utilized bioindicators in both environmental and human health studies. Lichen and bryophytes lack root structures and the capacity to store water, creating a dependence on moisture and nutrients scavenged from the atmosphere. By also lacking a protective cuticle, they absorb water and contaminants much like a sponge.

Biodiversity-based indices, including richness, relative abundance or dominance of sensitive lichen and bryophyte species are commonly used for mapping deposition of nitrogen (N)- and sulphur

(S)-containing pollutants. Species' sensitivities to H_2S, SO_2, acidic deposition, HNO_3, NH_3, NO_y, and the N- and S-containing aerosols have been well established through field studies and controlled fumigation experiments (Riddell et al. 2008; Riddell et al. 2012). Biodiversity indices usually correlate well with instrumented measurements of pollutant deposition (Gadsdon et al. 2010; Jovan et al. 2012), although some indices are intentionally non-specific, meaning they are not calibrated to track specific pollutants. In this case, biodiversity measures are interpreted as an integrated response to 'air quality' in general (Castro et al. 2014), which may provide a useful representation of human exposure as the human body integrates pollution from multiple sources.

Nitrogen, S, as well as metals (Wolterbeek 2002), radionuclides (Seaward 2002) and persistent organic pollutants (POPs) like polycyclic aromatic hydrocarbons (PAHs), dioxins and furans (PCDD/Fs), polychlorobiphenyls (PCBs) and polybrominated diphenyl ethers (PBDEs) (Augusto et al. 2013; Harmens et al. 2013) accumulate over time in lichen and bryophyte tissues, allowing their use as in-situ passive deposition monitors. Lichens and bryophytes tolerate exposure to many non-nutrient pollutants (e.g. heavy metals, radionuclides, POPs), and so typical biodiversity-based indices cannot be utilized for this group.

6.1 Air quality bioindicators: ways forward

There is clearly great potential for utilizing bioindicators in human health research; yet few scientists have done so. The use of bioindicator data in health studies has barely been explored, despite potential to overcome some of the most persistent data gaps in public health research on air quality. This potential can be explained by the fact that obtaining spatially and temporally representative air quality measurements is one of the most pervasive issues in health studies (Brauer 2010; Ribeiro et al. 2010) yet, for the most part, health research utilizes bioindicator maps tangentially or not at all. Bioindicators have the advantage of being living organisms and thus biologically reflecting the environment where they are growing. This information is not likely to be obtained through other monitoring methods, which solely represent physicochemical measures of pollutants. None of these research barriers are insurmountable. The main issue appears to be bringing together the right mix of skills. The proposed ways forward include the following:

Cross-sectoral collaboration is needed to foster information exchange and collaboration between bioindicator specialists and public health scientists. There is little crossover in the professional activities of these groups at present, and interdisciplinary workshops and meetings could further reduce this gap.

Future research should highlight the need to calibrate bioindicators with existing air monitoring stations or passive samplers, which are more flexible. While expensive to collect, investment in calibration data will facilitate the use of pollutant thresholds in bioindicator maps and also help define what time frame the bioindicator reflects, including how seasonal variations or sudden pollution episodes contribute to bioindicator values. Even if causality or mechanism cannot be established, an affordable bioindicator with the capacity to predict human health outcomes remains valuable for further research.

For large health research institutions, maintaining staff dedicated to data dissemination is critical for enabling access to detailed personal public health data. These intermediaries often help, for instance, by spatially joining bioindicator and health data, to keep confidential addresses for private residences.

Research that utilizes and cross-links resources that are already available, such as high-resolution maps from air quality and public health monitoring studies, should be encouraged. Also, lichens and bryophytes form the backbone of large-scale air quality monitoring programmes in both Europe (the International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests operating under the UNECE Convention on Long-range Transboundary Air Pollution) and the US (the US Department of Agriculture's Forest Inventory and Analysis Program).

7. Knowledge gaps and ways forward

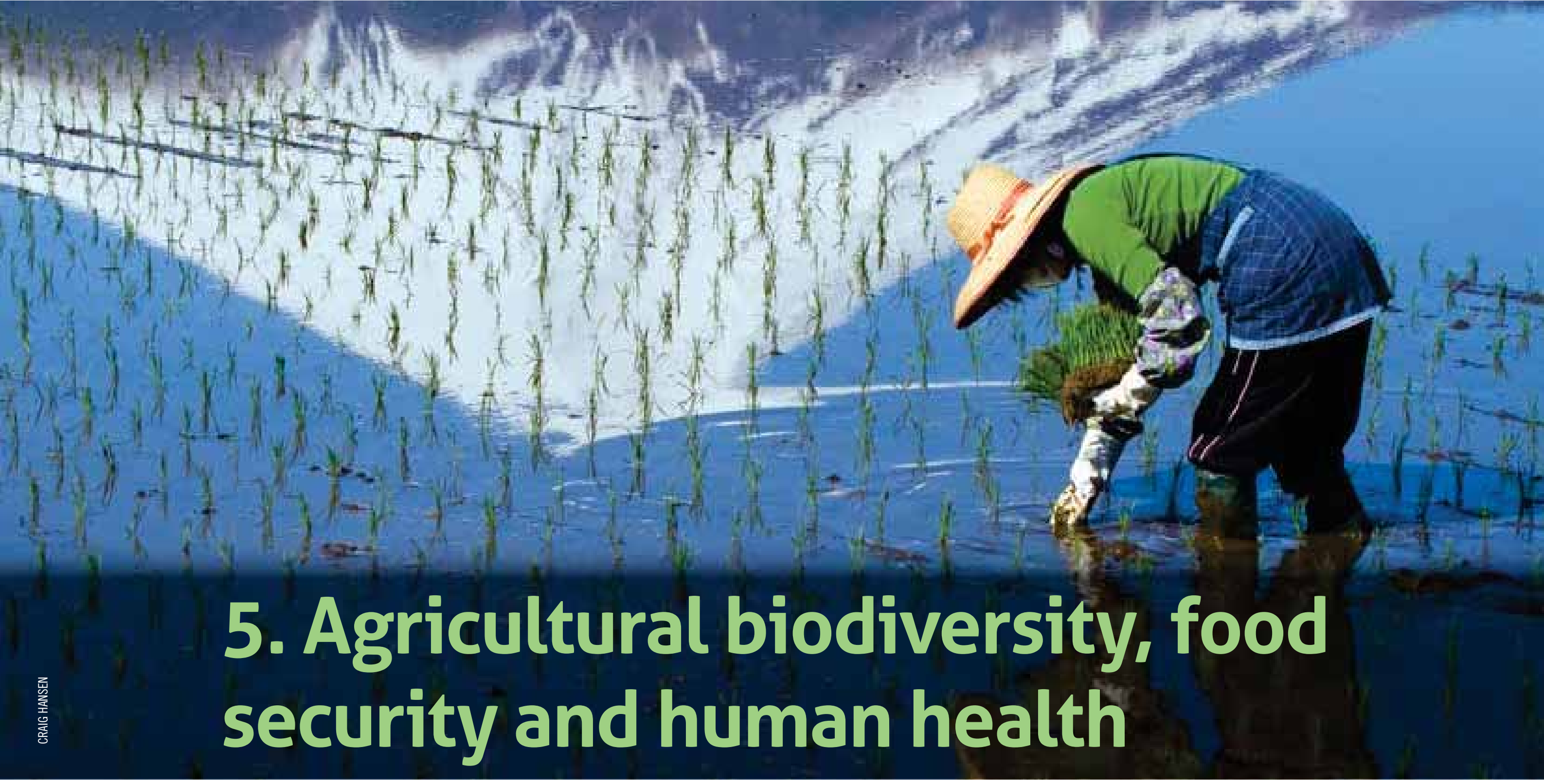
There are numerous gaps in knowledge related to biodiversity, including plant biodiversity (species-specific effects) and air quality. As there are numerous species globally, these gaps are felt across the world. However, leaf area is the dominant characteristic that affects many aspects of air quality. Thus, general magnitudes of impact can be assessed among plant communities based on leaf area. The individual species effects are most important in determining variations within plant communities, understanding the impacts of biodiversity and guiding vegetation management. There are gaps in all aspects of plant species effects on air quality, but some of the better-researched aspects are related to VOC emissions, which are species or genera dependent. Estimates and comparisons of pollen allergenicity among plant species also exist (e.g. Pettyjohn and Levetin 1997; Ogren 2000; Cariñanosa et al. 2014). One of the least understood aspects related to individual species characteristics and air quality effects relates to species-specific removal rates (deposition velocities) for various pollutants. In addition, while there are various studies relating air pollution to human health, there are few studies relating vegetation impacts to pollution concentrations and human health effects.

To facilitate air quality improvements through biodiversity and management of vegetation, there are various steps that managers and policy-makers could take. The first step could be to assess the local species composition and biodiversity as a basic foundation for understanding the local vegetation structure. The second could be to assess what impacts this current vegetation structure has on air quality (e.g. estimating pollution removal, VOC emissions, impacts on building energy conservation and emissions, etc). To aid in understanding the vegetation ecosystem services, various models exist (e.g. i-Tree). Policy-makers could also facilitate increased research to better understand the effects and impact of individual species on air quality.

Local vegetation management decisions can help improve air quality. Vegetation management strategies to help improve air quality include the following:

- Increase the amount of healthy vegetation (increases pollution removal).
- Sustain the existing vegetation cover (maintains pollution removal levels).
- Maximize the use of low VOC-emitting species (reduces O_3 and CO formation).
- Sustain large, healthy trees (large trees have greater per-tree effects).
- Use long-living tree species (reduces long-term pollutant emissions from planting and removal).
- Use low-maintenance species (reduces pollutant emissions from maintenance activities).
- Reduce fossil fuel use in maintaining vegetation (reduces pollutant emissions).
- Plant trees in energy-conserving locations (reduces pollutant emissions from power plants).
- Plant trees to shade parked cars (reduces vehicular VOC emissions).
- Supply ample water to vegetation (enhances pollution removal and temperature reduction).
- Plant vegetation in polluted or heavily populated areas (maximizes pollution removal and air quality benefits; however, specific vegetation designs need to be considered so that they do not increase local pollutant concentrations, such as near roadways).
- Avoid pollutant-sensitive species (improves plant health).
- Utilize evergreen species for particulate matter (year-round removal of particles).

Through proper design and management, plant systems and biodiversity can be utilized to enhance air quality and provide numerous other ecosystem services, and consequently improve the health and well-being of people and ecosystems across the globe.


CRAIG HANSEN

5. Agricultural biodiversity, food security and human health

1. Introduction

The world's population has increased from roughly 2.5 billion people in 1950 to more than 7 billion today (USCB 2013) and is anticipated to exceed 9 billion by 2050. This development, in parallel with global affluence and associated dietary shifts (Alexandratos and Bruinsma 2012; Tilman et al. 2011), has been accompanied by a parallel rise in demand for food and other agricultural products (Godfray et al. 2010). Food production is expected to have to rise by a further 70–100% by 2050 (Tilman et al. 2001; Foley et al. 2005; Green et al. 2005). Global food production systems have largely kept pace with population growth over the past 50 years due to conversion of natural ecosystems to agriculture, intensification of farming practices on existing agricultural lands, improved varieties of crops and breeds of animals, and improved agronomic practices (Wilby et al. 2009). From 1980 to 2001, global cereal production increased by 36% with a simultaneous increase of 34% in areas under permanent crop and in the use of nitrogen fertilizers (FAO 2003). While increases in food production have contributed to feeding an additional 4 billion people, improved human nutrition and reduced hunger prevalence from 33% to 18% over the past 40 years (Sanchez et al. 2005), the number of chronically or acutely malnourished people remain stubbornly high, still exceeding 800 million (FAO 2014). The improvements in food production (and consequent benefits in overall human health in many areas) have also generally been accompanied by a loss of biodiversity in agro-ecosystems, and led to new public health challenges.

An adequate supply of safe and nutritious food is one of the cornerstones of human health, and the ways in which biodiversity and food production are interrelated and influence each other are key aspects of this relationship. Agriculture and food production are also significantly implicated in the extent to which planetary boundaries have been or are likely to be exceeded with respect to nitrogen flows, water usage, and land use change (Rockstrom et al. 2009; Steffen et al. 2015), and in the negative effects of loss of biodiversity on human health described in other chapters of this volume.

This chapter focuses on the links between agricultural biodiversity, food security and human health. It covers both direct impacts, such as the loss of arable land and natural habitat, and health outcomes associated with modern agricultural practices. The relationships between biodiversity and nutrition are dealt with in a related chapter in this volume.

2. Agricultural biodiversity[1]

2.1 The contribution of agricultural biodiversity to human health

Agricultural biodiversity (often referred to as agrobiodiversity) includes all the components of biological diversity of relevance to food and agriculture, and those that constitute the agro-ecosystem: the variety and variability of animals, plants and microorganisms at the genetic, species and ecosystem levels, which sustain the functions, structure and processes of the agro-ecosystem (FAO/PAR 2011). Created, managed or influenced by farmers, pastoralists, fishers and forest dwellers, agricultural biodiversity continues to provide many rural communities throughout the world with stability, adaptability and resilience in their farming systems and constitutes a key element of their livelihood strategies (Altieri and Merrick 1987; Brush 1999; Jarvis et al. 2011).

Agricultural biodiversity plays a critical role in global food production and the livelihoods and well-being of all, regardless of resource endowment or geographical location. As such, it is an essential component of any food system. Productive agro ecosystems, both wild and managed, are the source of our food and a prerequisite for a healthy life, and agricultural biodiversity contributes to all four pillars of food security.[2] The sustainability of agroecosystems is dependent on the conservation, enhancement and utilization of biodiversity. Agricultural biodiversity provides the basic resources needed to adapt to variable conditions in marginal environments and the resources required to increase productivity in more favourable settings. Further, with global, especially climate, change, there will be increasing interdependence between farmers and communities all over the world, who will be ever more reliant on the global benefits agricultural biodiversity can provide (MA 2005; Frison et al. 2011; Lockie and Carpenter 2010). All too often, the food used for human consumption and the nutritional and health benefits biodiversity provides have been ignored (De Clerck et al. 2011). When these links are considered, biodiversity, agriculture and health can form a common path leading to enhanced food security and nutrition (Toledo and Burlingame 2006).

It has been estimated that some 7000 plant species have been used by humans at one time or another although some 82 crop species provide 90% of the energy currently consumed by humans (Prescott-Allen and Prescott-Allen 1990). From this total, 40% is provided by only three crops. Despite this homogenization of production systems, there remain several hundred neglected and underutilized crops with significant potential to support diversification, improve adaptability to change and increase resilience (Kahane et al. 2013). In contrast, about 40 livestock species in total contribute to today's agriculture and food production and only five species provide 95% of the total (FAO, 2007; Heywood 2013).

For aquaculture, it has been estimated that over 230 spp. of finfish, molluscs and crustaceans are utilized but that 31 species are responsible for 95% of production (85% of which takes place in Asia) (FAO 1996).[3] As discussed in the chapter on nutrition in this volume, crop, animal and aquaculture species diversity also contribute to dietary diversity, the variety of macro- and micronutrients needed by humans, and multiple livelihood benefits.

Genetic diversity plays a particularly important role in agriculture (FAO 2010). The development of new varieties and breeds depends on the use of

[1] In this chapter, agriculture is taken to include crop and animal production, and freshwater aquaculture for food and other goods and services. It does not include marine aquaculture and wild fish harvesting and covers forest production systems only insofar as they contribute to food production.

[2] The Committee on Food Security describes food security as existing when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life. It identifies four pillars of food security – availability, access, utilization and stability, and notes that the nutritional dimension is integral to the concept of food security. See: http://www.fao.org/fileadmin/templates/cfs/Docs0910/ReformDoc/CFS_2009_2_Rev_2_E_K7197.pdf

[3] See ftp://ftp.fao.org/docrep/fao/011/i0283e/i0283e02.pdf

Box 1. Risks to animal genetic resources

A total of 7616 livestock breeds from 180 countries are mentioned in the Food and Agriculture Organization (FAO)'s Global Databank for Animal Genetic Resources for Food and Agriculture. It has been estimated that 30% of these are at risk of extinction. In contrast to crops plants where significant populations of potentially valuable crop relatives exist in the wild, *The state of the world's animal genetic resources for food and agriculture* (FAO 2007) notes that "with the exception of the wild boar (*Sus scrofa*), the ancestors and wild relatives of major livestock species are either extinct or highly endangered as a result of hunting, changes to their habitats, and in the case of the wild red jungle fowl, intensive cross-breeding with the domestic counterpart. Thus, domestic livestock are the depositories of the now largely vanished diversity" (FAO 2007:6).

Box 2. Aquatic agroecosystems and human health

Aquatic agroecosystems, such as fish–rice systems of South and South-East Asia, contain a rich diversity of edible species. For many rural populations living in these areas, rice and fish are the main dietary staple. Aquatic animals are often the most important source of animal protein and are essential during times of rice shortages, providing essential nutrients that may otherwise not be adequate (Halwart 2006). Thus, wild and gathered foods from aquatic habitats provide important diversity, nutrition and food security. Recent studies on the utilization of aquatic biodiversity from rice-based ecosystems during one season only in Cambodia, China, Laos and Viet Nam found that 145 species of fish, 11 species of crustaceans, 15 species of molluscs, 13 species of reptiles, 11 species of amphibians, 11 species of insects and 37 species of plants were caught or collected (Halwart 2013; Halwart 2006; Halwart and Bartley 2005).

Bangladesh contains a great variety of inland water bodies, including beels, ponds, rivers, canals, ditches and rice paddy fields, which contain more than 267 freshwater fish species (Rahman 1989). In particular, small indigenous fish species (*Parambassis baculis, Parambassis ranga, Rohtee cotio, Esomus danricus, Corica soborna, Chanda nama, Amblypharyngodon mola, Channa punctatus, Puntius* ssp.) are a rich source of highly bioavailable nutrients, animal protein and some, with a high fat content, contain beneficial polyunsaturated fatty acids. Indigenous fish species, such as darkina (*Esomus danricus),* have a high iron, zinc and vitamin A content (Thilsted 2013; see also the chapter on nutrition).

Integrated aquatic agroecosystems demonstrate the many beneficial interactions between the different elements of biodiversity that enhance food production and the ecosystem services that support it while significantly increasing agricultural biodiversity and reducing production risks. Rice plants contribute to improved water quality and ensure temperatures for optimum prawn and fish production. Plants provide habitat and shelter for fish, reducing the risk of predation. Foraging on aquatic sediments, including pests and weeds, and the consumption of phytoplankton by fish enhances nutrient exchange between water and soil, and reduces the need for pesticides and fertilizers. Small indigenous fish species also tend to be preferred by farming households and constitute an important source of minerals, micronutrients and vitamins (Bunting and Ahmed 2014).[4]

[4] See also Climate change and adaptation and prawn-fish-rice agroecosystems, Landscapes Blog for People, Food and Nature http://blog.ecoagriculture.org/2014/07/14/climate-change-adaptation-and-prawn-fish-rice-agroecosystems/

the genetic diversity present in the target species. The continuing increases in productivity achieved over the past century have depended to a significant extent on the continuing improvements made by plant and animal breeders. The development and maintenance of different crop varieties, animal breeds and aquatic species' populations provide the variety of food products that human societies require. Their continued improvement provides the basis for meeting increased food demands and adaptability to changing production conditions and practices. The importance of maintaining genetic diversity is reflected in the global concern with the conservation and use of genetic resources, as evidenced by the publication of reports on the state of the world's plant, animal and forestry genetic resources (FAO 2007, 2010, 2014; see also Box 1), the work of the FAO Commission on Genetic Resources for Food and Agriculture, the establishment of the Global Crop Diversity Trust and the entry into force of the International Treaty on Plant Genetic Resources for Food and Agriculture.

Genetic diversity within production systems is essential for the provision of ecosystem services (Hajjar et al. 2008). Although production systems have become increasingly uniform, and dominated by a few varieties of major crops, many small-scale farmers grow and maintain a number of different traditional varieties or breeds. Reasons for maintaining genetic diversity include: stability and risk avoidance; adaptation and adaptability to variable, difficult or marginal environments and to environmental change; provision of key ecosystem services such as pest and disease control, pollinator diversity, below-ground diversity and soil health; meeting changing market demands, coping with distance to market and adult labour availability; dietary or nutritional value; and meeting cultural and religious needs (see review by Jarvis et al. 2011).

3. Agricultural production, land use, ecosystem services and human health

Agricultural crops or planted pastures have become the dominant form of land use, comprising almost onethird of terrestrial land (Scherr and McNeely 2008). Today more than one third (38%) of the terrestrial landscape has been converted for agriculture, with the majority (26%) of converted land dedicated to livestock production (Foley et al. 2011). In addition to food production from agriculture, between 1% and 5% of food is produced in natural forests (Wood et al. 2000). Ellis and Ramankutty (2008) have estimated that more than 75% of the earth's ice-free land shows evidence of alteration as a result of human residence and land use. Over 1.1 billion people, mostly dependent on agriculture, live within the world's 25 biodiversity "hot spots" (Cincotta and Engelman 2000; Myers et al. 2002). The ways in which humankind has influenced or managed the different biomes around the world has resulted in a wide diversity of production systems (Ellis et al. 2010), and each production system or combination has different features, both in terms of the biodiversity found within the system and associated impacts on human health.

Changes in land use and agricultural intensification have been two of the most important drivers of biodiversity loss in both natural and agricultural productions systems (MA 2005). In the section that follows, the major effects of these changes on agricultural biodiversity and human health are summarized, and alternative pathways to ensuring adequate food production in ways that support co-benefits are identified.

3.1 Land use, land conversion and intensification

3.1.1 Land use and the expansion of arable land

Heterogeneous patterns in land cover change have followed human settlement and economic development (Richards 1990; Grigg 1974; Roberson 1956). Over the past three centuries, roughly 12 million km^2 of forest and woodlands have been cleared, and 5.6 million km^2 of grassland and pastures have been converted (Richards 1990). At the same time, cropland areas have increased by 12 million km^2, and some 18 million km^2 (equivalent to the size of South America) are under some form of cultivation (Ramankutty and Foley 1998).

With land conversion has come significant biodiversity losses as complex forest, grassland and wetland communities were converted into highly simplified cropping landscapes. In addition to the health effects of simplification and homogenization, land conversion affects human health in five primary ways:

i) Change in the delivery of supporting and regulating services from natural habitat important for agricultural production;

ii) The loss of habitat for wild species, which contribute to diets in many parts of the world (reviewed in the chapter on nutrition);

iii) Increased interaction with disease host, vectors and reservoirs (discussed briefly here and reviewed in the chapter on infectious diseases);

iv) Loss of medicinal plants (reviewed in the chapter on traditional medicine);

v) Cultural ecosystem services and mental well-being associated with interactions with nature and landscapes (see the chapter on mental health in this volume).

Most land conversion is currently taking place in tropical forest regions, home to some of the highest levels of biodiversity globally and a critical biome regulating global ecosystem services. Since the 1980s, 55% of new agricultural land in the tropics has come from the clearing of forests (Gibbs 2010). Forest and woodlands are important carbon sinks, they play an important role in the regulation of climate (Shvidenko et al. 2005), water flow and water quality (Shvidenko et al. 2005) and are important sources of fibre and fuel for numerous communities (Sampson et al. 2005).

Land use change, particularly deforestation for agriculture, is a leading contributor of carbon dioxide (CO_2), the greenhouse gas that is the primary contributor to climate change. An estimated 1.3 T 0.7 Pg C year^{-1} of CO_2 is emitted as a result of tropical land-use change (Pan et al. 2011), and land-use change accounts for 20–24% of all CO_2 emissions annually (IPCC 2014). Although there is currently little agreement on the net biophysical effect of land-use changes on the global mean temperature, its biogeochemical effects on radiative forcing through greenhouse gas (GHG) emissions was found to be positive (Working Group I Chapter 8; Myhre and Shindell 2013). The impacts of climate change are expected to both affect and be affected by the agricultural sector, with rising global temperature exceeding the thermal tolerance of certain crops (Bita and Gerats 2013), more erratic precipitation patterns (Rosenzweig et al. 2001) and greater incidence of disease outbreaks (Rosenzweig et al. 2001).

With the most fertile lands already used for farming, land conversion for agriculture increasingly brings marginal and/or fragile lands

Box 3. Soil health and agricultural biodiversity

The importance of agricultural biodiversity in supporting soil health and associated regulating and supporting ecosystem services has been reviewed by Swift et al. (2004). The importance of diversity of soil biota and of the maintenance of all components of the soil food web, and of diversity within different levels has been described by Beed et al. (2011), Gliessman (2007) and Mäder et al. (2002). However, the amount of diversity that is needed or desirable is the subject of some debate and some authors have argued that, in functional terms, saturation is reached at fairly low levels of species diversity. There is growing evidence that natural and less intensive agricultural production systems have higher levels of diversity than those under intensive agriculture and that higher levels of diversity are associated with improved delivery of key ecosystem services. Swift et al. (2004) have noted the importance of maintaining total system diversity and of practices, such as conservation agriculture, and mulching, which ensure higher diversity levels in the soil.

under cultivation. Conversion of forested hillsides and the further expansion of arable farming into nutrient-poor tropical soils may lead to poor yields, with large losses in biodiversity (see Box 3 on soil health). It is expected that land conversion will continue to increase in some areas, particularly in biodiversity hotspots around the tropics where human population pressures are mounting (Myers 2000). This can also lead to increased incidence of infectious diseases, covered in a separate chapter in this volume. Other areas may see abandonment of marginal agricultural lands (Grau et al. 2004), and a forest transition with the return of significant areas of natural vegetation and biodiversity with land abandonment and replanting (Rudel et al. 2005).

3.1.2 Intensification and ecosystem services

Farmers are bringing more land under cultivation and intensifying land use on existing farmlands by removing fallow periods, hedgerows, ditches and green spaces, enlarging fields and expanding land under permanent cultivation (Stoate et al.

Box 4. Livestock intensification

As global incomes increase, diets increasingly shift from the protein derived from plant products to increased consumption of meat, dairy and eggs, adding pressure on farming systems to increase livestock production (Tilman et al. 2011). Global meat production is projected to more than double from 229 million tonnes in 1999/2001 to 465 million tonnes in 2050, while milk output is set to climb from 580 to 1043 million tonnes (FAO 2006). Already livestock production uses 30% of the earth's entire land surface, mostly permanent pasture but also including 33% of the global arable land used to produce feed for livestock (FAO 2006; Cassidy et al. 2013). While livestock makes an important contribution to food security, its increased consumption is also a contributing factor to the increase in noncommunicable diseases (NCDs) and can have negative impacts on biodiversity (as discussed in the chapter on nutrition in this volume).

Livestock feed crops (maize, soya) in low-diversity and high-intensity cultivation systems are a very inefficient use of resources and crop calories. For every kilogram of beef produced, 1 kg of feed is needed (USDA 2002). At present, 36% of calories produced by cropping systems is used for animal feed of which only 12% are ultimately used for human consumption (Cassidy et al. 2013). It has been estimated that if these calories were consumed by people directly, the current global food production system could feed an additional 4 billion (Cassidy et al. 2013), meeting our estimated population growth forecasts for 2050.

The conversion of land for pasture is a major driver of deforestation. For example, in Latin America, some 70% of former Amazonian forest has been turned over to grazing (FAO 2006). Widespread overgrazing disturbs water cycles, reducing replenishment of above-and below-ground water resources. Beyond land conversion, the livestock sector can also be deleterious to increasingly scarce water resources with negative implications for human health (McMichael et al. 2007). Animal wastes antibiotics and hormones, chemicals from tanneries, fertilizers and the pesticides used to spray feed crops contribute substantially to water pollution, eutrophication and the degeneration of coral reefs, while also posing health risks, such as antibiotic resistance (FAO 2006; Horrigan et al. 2002). The use of these products not only affects biodiversity but also has health consequences, for example, by affecting drinking water quality, increasing the risks for several types of cancer, undermining local fisheries – another important source of dietary protein – and contributing to endocrine disruption and reproductive dysfunction (Horrigan et al. 2002; see also chapter on freshwater in this volume).

2001; Wilby et al. 2009; Frison et al. 2011), as well as use of more agro-chemicals and inputs (see section 3.3.1). Although small in size, fragments of natural habitat within agricultural landscapes are important for the provision of a number of agricultural ecosystem services (Mitchell et al. 2013) and for maintaining wildlife habitats and corridors, which can contribute to sustainability and conservation. The supporting and regulating services upon which agriculture depends include pollination, pest control, soil health, water regulation and nutrient cycling, largely provided by associated biodiversity in and around production systems (Kremen et al. 2007).

It has been estimated that, based on current trends of greater agricultural intensification in richer nations and greater land clearing (extensification) in poorer nations, an estimated 1 billion ha of land may be cleared globally by 2050 (Tilman et al. 2011). However, according to FAO estimates, only about 70 million ha of additional land is likely to be used by 2050 (FAO/PAR, 2011). In contrast, if the crop demand in 2050 was met by moderate intensification focused on existing croplands in countries where potential exists, combined with the use of appropriate technologies, only some 0.2 billion ha would be needed.

The scale and nature of land conversion is also important to the continuing provision of ecosystem services. Many essential ecosystem services are delivered by organisms that depend on habitats that are segregated spatially or temporally from the location where services are provided, such as farmed fields (Kremen et al. 2007; Mitchell et al. 2013). Fine-scale green spaces such as hedgerows, ditches, green strips are critical habitats for important agricultural biodiversity such as bees, birds, arthropods and mammals, and a source of many of the ecosystems services important for agriculture (Ricketts 2004, 2008; Kremen et al. 2007, 2012; Kremen and Miles 2012; Horrigan et al. 2002; Mitchell et al. 2013). Management of organisms contributing to ecosystem services requires consideration not only of the local scale where services are delivered (i.e. farmed fields), but also the distribution of resources at the landscape scale, and the foraging ranges and dispersal movements of the mobile agents (Kremen et al. 2007). Two examples of the contribution of agricultural biodiversity to ecosystem services are pollination and pest and disease control.

3.2 Pollination

The importance of insect pollination for agriculture is unequivocal, and yet global pollinator populations are in significant decline (Potts et al. 2010) with potential consequences for pollination-dependent crop yields. Globally, 35% of crops depend on pollinators (Klein et al. 2007) with an additional 60–90% of wild plant species also requiring animal pollination (Husband and Schemske 1996; Kearns et al. 1998; Ashman et al. 2004). Pollination services also contribute to the livelihoods of many farmers. It has been estimated that in 2005, the total economic value of pollination worldwide was €153 billion, equivalent to 9.5% of the value of the world agricultural production used for human consumption. In terms of welfare, the consumer surplus loss was estimated at between €190 and €310 billion (Gallia et al. 2009).

Many of the crops for which pollination is essential, including fruits and vegetables, are important sources of micronutrients and vitamins (Eilers et al. 2011). Pollinated crops contribute 90% of the vitamin C, 100% of lycopene and almost all of the antioxidants β-cryptoxanthin and β-tocopherol, the majority of the lipid vitamin A and related carotenoids, calcium and fluoride, and a large portion of folic acid in our diets (Eilers et al. 2011). In terms of calories, approximately one third of the human diet comes from insect-pollinated plants (USDA 2002; Tscharntke et al. 2012). Many forage crops for livestock (e.g. clover) are also pollination dependent (see the chapter on nutrition for a case study on pollination).

For pollinated crop species, field size and distance to natural habitat edges is a strong predictor of fruit set (Klein et al. 2003; Ricketts et al. 2004, 2008). As hedgerows and green spaces have been eliminated from farming landscapes, and pesticide use has expanded, problems of ensuring adequate pollination have increased. There is an increasing trade in honey bees to provide pollination services, although this is facing problems that appear to result from an unknown combination of habitat loss (Naug 2009), chemical use (neonicotinoids) (Maus et al. 2003) and disease resulting in colony collapse (reviewed in Ratnieks and Carreck 2010). Wild insect pollinators are often much more effective than honey bees but their delivery of this essential ecosystem service is also strongly compromised by habitat loss, land conversion and chemical usage.

3.3 Pest control

A major health concern associated with agricultural intensification is the increased use of pesticides. Among them, direct exposure to some pesticides have been associated with neurological, reproductive and genotoxic effects (Sanborn et al. 2007) and, in some cases, prolonged exposure to certain pesticides has been found to increase the risks for certain cancers, including non-Hodgkin lymphoma, leukaemia, brain and prostate cancers, among others (Bassil et al. 2007).

The simplification of landscapes through the enlargement of fields and loss of natural habitat areas also influences natural pest control services provided by associated biodiversity. These services help to reduce pest population numbers without the use of pesticides. Non-crop areas such as meadows, hedgerows and forest patches provide a habitat for a wide range of natural enemies of crop and animal pests and diseases (birds, aphids, etc.). Interspersion of natural habitats in the landscape matrix promotes the movement of natural enemies between crop and non-crop habitats, which is lost in landscapes dominated by arable cropland (Bianchi et al. 2006).

In a review of studies, Bianchi et al. (2006) showed that in 74% and 45% of cases, respectively, natural enemy populations were higher and pest pressure lower in complex landscapes versus simple landscapes. Pest predator activity was equally associated with herbaceous habitats, wooded habitats and landscape patchiness (Bianchi et al. 2006), suggesting that maintaining all three habitat types are important for the provision of pest control services. In structurally complex landscapes, Thies and Tscharntke (1999) showed that parasitism was higher and crop damage was lower than in simple landscapes. Landscape diversity can also be an effective way to control non-native introduced crop pests (an emerging threat for many agricultural systems) through enhanced pest control services by native wildlife (Gardiner et al. 2009).

The value of diversity and the importance of maintaining natural prey/predator relations for pest control have been demonstrated in many crops (Hajjar et al. 2008). Gurr et al. (2003) list examples that range from the local field level to landscapes, and integrated pest management (IPM) programmes in Asia have shown that conserving arthropod diversity is a key ingredient of their effectiveness. Pretty et al. (2006) analysed 62 IPM projects in 21 countries and found that in 47 of them yields increased by an average of 42% while pesticide use declined by 71%.

Genetic diversity can also make a significant contribution (Finckh and Wolfe 2006) to pest and disease control. Large-scale deployment of mixtures of crop varieties in barley and rice have demonstrated that, even with relatively few components, improvements in both yield and yield stability can be achieved (Wolfe et al. 1981; Zhu et al. 2000). Further work by Jarvis and collaborators (e.g. Mulumba et al. 2012) has shown that diversity of traditional crop varieties in crops as diverse as banana, maize and bean improves the stability of production without a reduction in the crop productivity. Tooker et al. (2012) have described the use of genotypically diverse variety mixtures for insect pest management. The use of genetic diversity to reduce the impact of epidemics has been described by De Vallavieille-Pope (2004). The use of diversity-based approaches to pest management in Africa are also described in Abate et al. (2000).

Crop management practices can also influence the efficiency of pest control services. Intercropping and inclusion of non-crop strips within fields have been shown to increase the abundance of spiders (important pest predators) by 33% (reviewed in Sunderland and Samu 2000), whereas management practices such as undersowing, mulching and reduced tillage were shown to enhance spider abundance by 80% (reviewed in Sunderland and Samu 2000). Temporal and spatial rotation of crops on fields is another important technique used to reduce the build-up of pathogens in soils and spread between plants (Abawi and Widmer 2000).

Reduced pest activity not only increases potential food production, but it may also reduce or eliminate the need for pesticides and reduce the presence of deleterious compounds associated with specific pests.

3.3.1 The use of pesticides and fertilizers in agricultural production

The negative effects of pesticides on human health, biodiversity and agricultural biodiversity have been well documented. Pesticides affect almost all living organisms and it has been estimated that more than 95% of herbicides and insecticides sprayed over agricultural fields reach a destination other than their target species (Tyler Miller 1994). Pesticides can be carried away by runoff water, seepage and leaching into ground-water, streams and aquatic environments, and through soil erosion. Through drift or evaporation, air can transport them for short and long distances, contaminating other areas, including wildlife (Cornell University 2001b; National Park Service 2014; Papendick et al. 1986). The following examples illustrate the effect of pesticides on agricultural biodiversity:

1. As persistent soil contaminants, pesticides negatively affect soil biota leading to lower organic matter content and reduced water retention, the latter reducing yields in drought years (Lotter et al. 2003). The reduction in soil- dependent ecosystem services, such as carbon and nitrogen cycling, leads to a situation of increased dependence on externally derived chemical inputs to support production – in fact, a negative feedback loop. The overall long-term effect of pesticides is a reduction in soil biodiversity (Johnston 1986). Pesticides in the soil also reduce the symbiotic efficiency of nitrogen-fixing rhizobia and host plants. More specifically, the insecticides DDT, methyl parathion, and especially pentachlorophenol have been shown to interfere with legume–rhizobium chemical signalling. The environmental consequences are an increased dependence on synthetic nitrogenous fertilizers, reduced soil fertility, and unsustainable long-term crop yields (Fox et al. 2007).

2. Because of their indiscriminate mode of action, herbicides have a direct negative effect on plants that occur in and around agricultural production systems. These include crop wild relatives and plants used for integrated pest management strategies, such as the push – pull system. A number of pesticides have also been shown to have some direct harmful effect on plants, including poor root hair development, shoot yellowing and reduced plant growth (Walley et al. 2006).

3. It has been estimated that farmers in the United States (US) lose at least $200 million a year from reduced crop pollination because pesticides applied to fields eliminate about a fifth of honeybee colonies in the US and harm an additional 15% (Tyler Miller 2004). Henry et al. (2012) found that, even with very low levels of the pesticide thiamethoxam, a neonicotinoid insecticide, in the bee's diet a high proportion of bees (more than one third) suffered from orientation disorder and were unable to come back to the hive, putting the colony at risk of collapse (colony collapse disorder) (see also Whitehorn et al. 2012). The pesticide concentration was much smaller than the lethal dose currently used, and its application, together with clothianidin and imidacloprid, was restricted by the European Union in April 2013 (Wall Street Journal 2013).

The repeated application of many of the chemicals used as pesticides increases pest resistance, while its effects on other species can facilitate the pest's resurgence (Damalas and Eleftherohorinos 2011). This is true not only of fungicides, insecticides and bacteriocides but also of herbicides. The law of diminishing returns comes into force and requires increasing use of such pesticides with decreasing beneficial effects and increasing detrimental effects on both the environment and human health.

The pesticide production industry is dynamic and able to develop, test and market an increasing range of chemical compounds, which have tended to become more specific and to have fewer deleterious side-effects. However, many pesticides remain generic with respect to the class of organism affected. There are now established international and national processes aimed at limiting the use of pesticides that have unacceptable negative effects on the environment or humans. The "Stockholm Convention on the Protection of Human Health and the Environment from Persistent Organic Pollutants (POPs)" came into force in 2004. It restricts and ultimately aims to eliminate the production and use of listed chemicals. This Convention also promotes the use of both chemical and non-chemical alternatives to POPs. Twelve chemical compounds – "the dirty dozen" – were on the Convention's original list of POPs. Nine of the 12 are pesticides (Gilden et al. 2010; UNEP 2005), including DDT (which is still used to control malaria). To date, ten more POPs have been added to this list and others are under review (UNEP 2013). Advances in agrochemistry have generally allowed pesticides to become more species-specific and to reduce their environmental impact. Moreover, the amount applied has declined in many cases, sometimes by 99% (Lamberth. et al 2013). The global spread of pesticide use, however, including the use of older or obsolete pesticides that have been banned in some jurisdictions, continues (Kohler and Triebskom 2013).

It is likely that most farmers use pesticides of some kind or other at some stage in their production (Alavanja 2009). Even many small- scale farmers in developing countries will use some pesticides and this can create major health problems through lack of appropriate equipment or knowledge, or through the use of outdated products. The US Environmental Protection Agency's (EPA) report on Pesticides Industry Sales and Usage (2006 and 2007 Market Estimates) reports that the amount of pesticide used worldwide was approximately 2.36 billion kg on average in 2006 and 2007, of which more than 0.5 billion kg (21%) was used in the United States. Herbicides (including plant growth regulators) accounted for the largest portion of total use, followed by other pesticides, insecticides and fungicides. Although the total global consumption of pesticides increased in 2007 (US Environmental Protection Agency 2011), there is evidence that countries can make a significant difference through their legislation and regulations to the amounts of pesticide used. For example, Indonesia reduced expenditure on pesticides (an estimate of total amount used) from a high of US$ 120–160 million in the period from 1980–1987 to US$ 30–40 million in the following 5 years.

It has been estimated that as many as 25 million agricultural workers in the developing world, where programmes to control exposure are limited or non-existent (Alavanja 2009), experience unintentional acute pesticide poisoning each year (Jeyaratnam 1990). While the acute effects of pesticides are well documented in the literature, especially with respect to organophosphate poisoning (Sanborn et al. 2004), it is much less easy to assess the chronic effects of pesticide exposure. Sanborn et al. (2004 and 2012) conducted systematic reviews to establish whether chronic exposure to pesticides had adverse health effects. Many of the reviewed studies showed positive statistically significant associations between health problems and pesticide exposure. The continuing presence of pesticides in food, water and soil is also responsible for significant risks to health (U.S. Environmental Protection Agency 2007).

Depending on their nature, properties and mode of use, exposure to pesticides can have a wide range of negative health effects (Cornell University 2001a). These include the following:

- Reproductive effects: effects on the reproductive system or on the ability to produce healthy offspring;

- Teratogenic effects: effects on unborn offspring, such as birth defects;

- Carcinogenic effects: produces cancer in living animal tissues;

- Oncogenic effects: tumour-forming effects (not necessarily cancerous);

- Mutagenic effects: permanent effects on genetic material that can be inherited;

- Neurotoxicity: poisoning of the nervous system, including the brain;

- Immunosuppression: blocking of natural responses of the immune system responsible for protecting the body.

The direct negative effects of pesticides on biodiversity and human health are numerous but it should be recalled that there have also been very tangible benefits to human health from the use of pesticides and insecticides, such as in malaria control programmes. However, insecticide resistance in malaria vectors was also reported in 53 of 65 reporting countries around the world since 2010. The most commonly reported resistance is to pyrethroids, the most frequently used insecticide in malaria vector control (WHO 2014).

The development of resistance in disease-producing organisms, or in vectors of human disease, as a result of pesticide overuse is one example where health problems can be combined with ecological imbalance and the development of large pest populations. The use of herbicides in rural areas can also have associated negative effects by reducing the availability of many gathered foods and thus deprives communities of important sources of dietary diversity. The same is true of the negative effects of pesticides on pollinators and the availability of honey in rural areas. More generally, the use of pesticides as a part of simplified agricultural systems, while increasing the production of major staples, can lead to production systems that are more vulnerable to change and stress, resulting in much greater fluctuations in yield, which renders farmers and

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rural communities liable to complete losses in production and loss of food security.

Fertilizers

The overuse of synthetic fertilizers has major negative effects on biodiversity, particularly freshwater and marine biodiversity and soil biota. It also has negative effects on human health, most obviously perhaps through pollution of groundwater and reduction in the availability of unpolluted fresh water. As with pesticides, there are points of interaction between loss of biodiversity and human health such as through the damaging effect of algal blooms and the increased frequency of toxic phytoplankton as described in the chapter on freshwater in this volume. The increasing size of marine dead zones also has a significant negative effect on the availability of fish for human consumption. While the application of synthetic fertilizers makes a significant contribution to improving overall food production and may be especially important in parts of Africa, for example, overuse has created major environmental problems in Asia. Large-scale synthetic fertilizer use is often associated with reduced adaptability and resilience in production systems and, in some stress situations, with reduced yield stability. Both synthetic fertilizers and pesticides can create negative feedback loops in which the reduced agricultural biodiversity associated with their use is accompanied by production problems associated particularly with loss of soil biota.

The negative effects of synthetic fertilizers on soil biota, soil acidification and groundwater pollution can be significant (Osborne 2011). Nitrogen that is not taken up by plants is transformed into nitrate, which is easily washed off the soil into watercourses or leached through soil into groundwater (Jackson et al. 2008; Barabasz et al. 2002). Nitrate levels above 10 mg/L in groundwater can cause acquired methaemoglobinemia in infants (also called "blue baby syndrome"), which leads to an overall reduced ability of the red blood cell to release oxygen to tissues, possibly leading to tissue hypoxia (Knobeloch et al. 2000; Self and Waskom 2013). High N fertilizer rates applied to arable, grassland and horticultural soils can also lead to the accumulation of nitrites and organic nitrogen compounds such as amines, nitro and nitroso compounds, including nitrosamines and nitrosamides (Barabasz et al. 2002).

Many studies have shown that mineral fertilization strongly affects both the number of microorganisms in the soil and the make-up of communities of soil microorganisms (Barabasz et al. 2002). Use of mineral fertilizers can also lead to increased heavy metal accumulation in soils, and potential health problems have been identified in connection with increased levels of cadmium, arsenic, lead and mercury. Eutrophication is also a major problem caused by the excessive inputs of phosphorus and nitrogen in lakes, reservoirs, rivers and coastal oceans (Smith and Schindler 2009, see also the Box on eutrophication in the chapter on freshwater).

3.4 Non-food crops

The demand for non-food crops has grown with the population and increasing prosperity. This has resulted in the conversion of larger areas of land for the production of (what some consider) "luxury" foods (e.g. coffee, tea, cacao), fibres (e.g. cotton), biofuels and oil (e.g. palm oil, rapeseed). Many of these crops grow exclusively in tropical climates (e.g. coffee, tea, cacao, oil palm) with production areas occurring almost wholly within areas identified as biodiversity hotspots (Myers et al. 2000), suggesting that production of such crops may have an environmental impact disproportional to its area (Donald 2004). The expansion of production of these crops in the twentieth and twenty-first centuries has come at great expense to local biodiversity (reviewed in Donald et al. 2004).

3.5 Impacts of agricultural intensification on human health

Agricultural intensification has involved the use of increasingly productive crop varieties and animal breeds, combined with the continually expanding use of chemical inputs, fossil fuel energy and water in both plant and animal production systems. The most important chemical inputs have been pesticides of many different types and fertilizers. Fossil fuel energy inputs have included mechanization of cultivation and harvesting, and the use of more intensive animal production systems. Food transport and processing have also become increasingly important aspects of the overall food system with consequences both for human health and agricultural biodiversity.

Box 5. Case study: biofuels

Crops for industrial use, including biofuels, make up 9% of crops by mass, 9% by calorie content, and 7% of total plant protein production, diverting a considerable quantity of food away from human consumption (Cassidy et al. 2013). In 2000, biofuel production alone represented 3% of crop production and is estimated to have increased more than 450% (in terms of litres produced) between the year 2000 and 2010 (WWI 2009), suggesting that increasing areas of land are being dedicated to the production of intensively managed corn, vegetable oils and sugarcane (Cassidy et al. 2013). Based on biofuel statistics from 2010, ethanol production from maize in the United States and from sugarcane in Brazil alone now represents 6% of global crop production by mass and 4% of calorie production (FAPRI 2011). Although biofuels are meant to help reduce the dependence on carbon-dense energy sources and reduce carbon emissions to mitigate climate change, the production of food crops for biofuels can have additional negative impacts on human health associated with (i) intense production techniques (i.e. air quality from forest burning, high chemical use and contamination of waterways) and (ii) diversion of crop calories away from the food production system. In addition to biofuels, significant portions of cultivated land are dedicated to the production of fibres, in particular cotton, as described in the chapter on freshwater.

Box 6. Case study: vegetable oils

Vegetable oils are among the most rapidly expanding agricultural sectors (Clay 2004), and more palm oil is produced than any other vegetable oil (Carter et al. 2007). A native of West Africa, oil palm *(Elaeis guineensis)* is grown across more than 13.5 million ha of tropical, high-rainfall, low-lying areas, a zone naturally occupied by moist tropical forest, the most biologically diverse terrestrial ecosystem on earth (Corley and Tinker 2003, MEA 2005). Palm oil has some of the world's largest plantations, sometimes exceeding 20000 ha (Donald 2004), cut out of the tropical rainforests of Indonesia, Malaysia and increasingly in Latin America. This has resulted in extensive clearing and burning of carbon-rich forests and peat lands, contributing to biodiversity loss, poor air quality affecting respiratory health particularly in South-East Asia, and adding CO^2 to the atmosphere (Clay 2004). Examination of palm oil cultivation in contrast to shaded coffee, pasture and natural forest found that palm plantations supported extremely low levels of birds, lizards, beetles and ant communities (Power and Flecker 1998; Chung et al. 2000; Glor et al. 2001).

Per unit area, palm oil is the highest-yielding vegetable oil crop; the current global production of oil palm fruit is estimated at 97.7 million tons, produced from 10.7 million ha; production is increasing by 9% every year (Donald 2004). Palm oil now makes up about 21% of the world's production of edible oils and fats, second only to soybean oil. The oil is used in the manufacture of cooking oil, margarine, soap and cosmetics, and it has industrial uses. As a substitute for diesel, palm oil is less suitable than other vegetable oils owing to its high viscosity, lower energy density and high flash point (Agrawal 2007). However, oil palm gives high yields at low prices, and hence is likely to be important in meeting biofuel demand (Carter et al. 2007; Koh 2007).

Specialization in one or a select number of crop or animal species has reduced agricultural biodiversity, affecting ecosystem services and human health (Frison et al. 2011). The introduction of invasive alien species can also have negative impacts on biodiversity, terrestrial and aquatic agriculture, and related provisioning and regulating ecosystem services (Pejchar and Mooney 2009). As discussed in the chapter on freshwater, these impacts extend to human health. These trends can also affect the diversity of foods being produced for human consumption and alter agro-ecological processes (Kremen and Miles 2012 and references therein). Intercropping of species and agroforestry practices (the maintenance of perennials in fields) have been shown to enhance above- and below-ground associated biodiversity, soil quality, water-holding capacity, weed control, disease and pest control, pollination, carbon sequestration, and resilience to droughts and hurricanes (reviewed in Kremen and Siles 2012).

There is also concern that industrialized farming systems are vulnerable to the same disease risks as crop monocultures. The level of genetic diversity in livestock breeds has fallen dramatically over the past century as a result of intense selection. In cattle, the Holstein breed dominates production in the West and intensive sire selection is leading to rapid inbreeding rates with a few sons of sires and grandsires dominating US populations (Holstein Assoc. USA 1986). Over the past 100 years, approximately 28% of livestock breeds have become rare, endangered or extinct globally (Notter 1999). This is particularly worrisome as genetic diversity is required to meet current production needs in various environments, to allow sustained genetic improvement, and to facilitate rapid adaptation to changing breeding objectives (Notter 1999). Modern agricultural production systems decouple agriculture from the surrounding environment, controlling feed, water, temperature and disease in large industrial complexes, selecting for animals with very little environmental tolerance. In the interim, we will lose breeds with a range of environmental tolerances (Tisdell 2003). As climate change progresses, the future will not look like the present and we will need genetic diversity to adapt to these changing conditions.

3.6 Alternative production pathways

The negative effects of modern intensive agriculture on the environment and human health, together with concerns about the unsustainable nature of many of the practices (e.g. with regard to water and phosphate use), the continuing failure to deal with malnutrition and the need to confront the challenges of climate change, have led to the identification of an increasing number of alternative approaches to agricultural production (e.g. Baulcombe et al. 2009; PAR/FAO 2011; FAO 2011; de Schutter 2010). The assessment that the food systems in place are no longer "fit for purpose" has been reflected in growing consumer concerns and the growth of civil society groups concerned about securing healthy and safe food production (Rosin et al. 2012).

Alternative approaches to ensuring sufficient production to meet human needs in environmentally safe ways are broadly based on enhancing the use of biological processes in agriculture. There are many alternative approaches and concepts variously identified as agroecology, ecological intensification or, more generally, as an ecological approach to agricultural production (Altieri et al. 1995; De Schutter 2010; FAO/PAR 2011). Ecological approaches are characterized by minimal disturbance of the ecosystem, plant nutrition from organic and non-organic sources, and the use of both natural and managed biodiversity to produce food, raw materials and other ecosystem services. This way, crop production not only sustains the health of farmland already in use, but can also regenerate land left in poor condition by past misuse (FAO 2011). This approach to agricultural production emphasizes the importance of maintaining natural ecosystem services and function in agricultural production systems rather than replacing them with external inputs.

There are a wide range of ecologically based options including conservation agriculture (Kassam et al. 2009), organic agriculture (Badgley et al. 2007), integrated pest management (IPM), integrated plant nutrition systems, ecoagriculture (Scherr and McNeely 2007), sustainable crop production intensification (FAO 2009) and agroecology (Wezel et al. 2009). Many of these have already been deployed in large production areas although they are yet to be universally accepted or adopted, and each has its own community of advocates and detractors.

Ecological approaches to agricultural intensification make increased use of agricultural biodiversity and are expected to create conditions that will support the maintenance of biodiversity as a whole and improve human health, either directly or indirectly. Some of the features of such approaches with respect to agricultural biodiversity and to human health are illustrated in the section that follows.

4. Food production, food security and human health

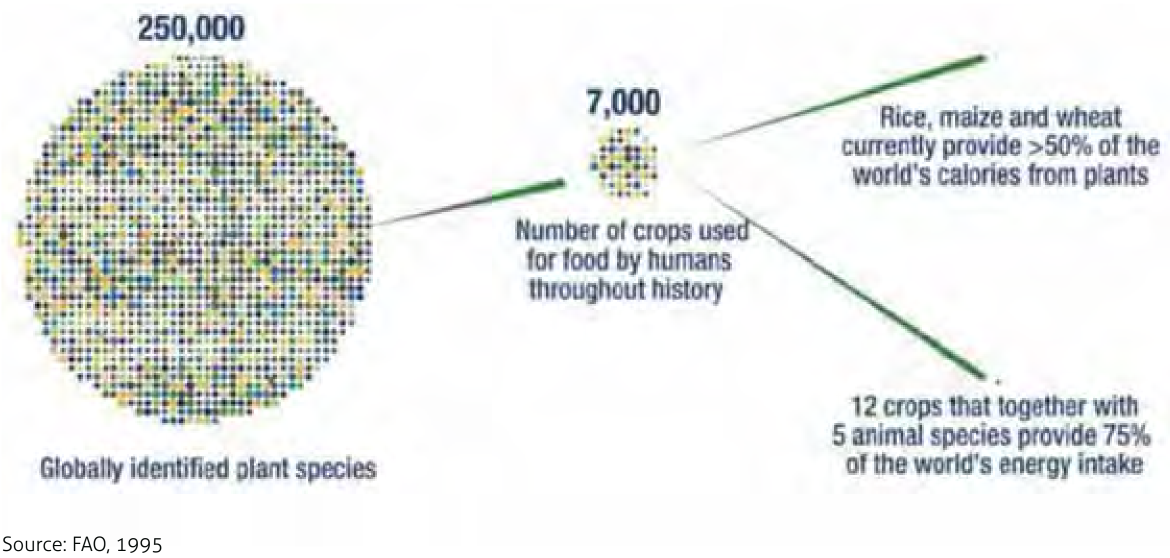
4.1 Agricultural biodiversity and food production

Many barriers and challenges continue to hinder the optimum utilization and sustainable management of agricultural biodiversity, which have caused it to be relegated to a minor role in agriculture and health (Hunter and Fanzo 2013). This neglect of agricultural biodiversity continues to come at a great cost to national health-care budgets, the global environment and society in general (see chapter on nutrition). Globalization and the simplification of agriculture, population increase and urbanization, along with public policies that continue to provide perverse incentives for unsustainable food production, have changed patterns of food production and consumption in ways that profoundly affect ecosystems and human diets, and have led to increasingly dysfunctional food systems. High-input industrial agriculture and long-distance transport increase the availability and affordability of refined carbohydrates and fats, leading to an overall simplification of diets and reliance on a limited number of energy-rich foods (Figure 1). This has also resulted in a considerable disconnect between diet and local food sources, a situation that threatens the continued existence of valuable agricultural biodiversity and the knowledge associated with it.

The development of widely adapted, highly uniform crop and livestock varieties has played a major part in the homogenization of agriculture. Such varieties or breeds can be grown and produced over very wide areas (many millions of hectares) owing partly to their broad adaptation and partly to the homogenization of agricultural production systems that can be achieved through chemical inputs and irrigation. The use of genetic modification and production of genetically modified organisms (GMOs) has added a dimension that has been the subject of substantial controversy (Letourneau and Burrows 2010; Costa-Font et al. 2010). The implications for human health of the widespread adoption of commercialized edible GMOs, including soy, maize and oilseed rape, is also disputed (summarized in De Vendômois et al. 2010 and references therein; Dona and Arvanitoyannis 2009). Certainly some of the practices associated with their use may have undesirable side-effects such as the widescale use of herbicides. However, others have suggested that GMO crop varieties reduce pesticide use and result in positive health benefits (Phipps and Park 2002). There are also concerns with respect to the unplanned spread of novel genes into wild crop relatives or to traditional varieties, especially in centres of crop diversity (Stewart et al. 2003). This unplanned spread could have significant negative consequences for existing patterns of within-species diversity, changing fitness levels of populations and varieties, and hence their potential long-term survival and evolution.

Shifts to monoculture or low diversity cropping systems in turn have led to the homogenization of global food production and the loss of regional and endemic crop types, while the adoption of global staple crops is changing people diet as many diets shift towards common starchy energy-dense foods crops in place of traditional crops or varieties (Padulosi et al. 2002; Malaza and Howard 2003; Adoukonou-Sagbadja et al. 2006; Smale et al. 2009). Such shifts have led to a global trend

FIGURE 1: The limited use of plant species diversity in agriculture



Source: FAO, 1995

of increased quantities of food calories, proteins and fat for human consumption, but they are increasingly sourced from a handful of energy-dense foods (Khoury et al. 2014). Consequently, national food supplies worldwide became more alike in composition, correlated with an increased supply of several globally important cereal and oil crops, and a decline of other cereal, oil and starchy root species. The increase in homogeneity worldwide portends the establishment of a global standard food supply, which is relatively species-rich with regard to measured crops at the national level, but species-poor globally (Khoury et al. 2014).

Agricultural homogenization not only affects diets, but potentially the resilience of global food systems. Such cropping patterns make both local and global production landscapes vulnerable to wide sweeping pest and disease outbreaks. As landscapes become increasingly similar in the crop composition, pests and pathogens, including those that are invasive, have increasingly large and connected cropland areas to infect and infest – both through natural dispersal and through increasingly integrated transportation and trade pathways. This can be seen in the recent epidemics of virulent yellow wheat rust, *Puccinia striiformis* f. sp. *tritici* that have appeared in new areas, e.g. eastern USA (Chen 2005), South Africa (Boshoff et al. 2002) and Western Australia (Wellings et al. 2003), as well as Central and northern Europe (Flath and Barthel 2002; Hovmoller and Justesen 2007). The vast and expansive spread of diseases affecting a small number of globally important crops can have important consequences for both local and global food supplies and human health (Hovmoller et al. 2008).

Such generalizations (Figure 1) mask the diversity of food crops, animal breeds, fish populations and genetic diversity that is still maintained and further developed by small-scale farmers, pastoralists and fisherfolk worldwide, and which is available and produced in many of the world's food production systems. Crop and livestock production systems that are often the target of agricultural development are in reality often elements of a larger landscape that comprises a broad range of wild, weedy and feral species that not only play critical roles in securing food production and ecosystem function but which may also contribute significantly to human diets, food security and health, such as many of the wild edible species found in and around aquatic agricultural systems or forests. Wildlife is consumed as bushmeat, and wild leafy and fruit species, and other edible species such as insects and mushrooms found in and around agricultural fields play an important role in feeding populations in many parts of the world (PAR/FAO 2011). Despite potential health benefits of bushmeat consumption, as the nutrition chapter also indicates, health risks associated with its unsafe handling, storage and growing illegal trade must also be carefully considered (see also the chapter on nutrition in this volume). Agricultural intensification has also often upset the balance maintained by rural communities between sustainably managed natural areas and farmed areas, leading not only to reductions in uncultivated areas but also overexploitation of the resources that remain.

4.1.1 Mixed farming; crop and fish and agroforestry – increasing species diversity

Diverse production systems with a number of different productive components themselves confer multiple benefits. The forms that these can take are many and varied. For example, home gardens, which are characterized by high levels of species diversity in a relatively small space, are highly productive with multiple livelihood, health and biodiversity maintenance benefits (Galuzzi et al. 2010; Box 7 on home gardens). Diversity in livestock production has been shown to confer benefits through improved provision of nutrients, overall productivity, system resilience and income (Morton, 2007). The aquatic rice-based agroecosystems of South and South-East Asia improve ecosystem function, nutrition and income in many different farming systems (Halwart 1998; Pullin and White 2011; see also Box 2). Integrating trees into agricultural environments helps to realize the full potential of agroforestry ecosystem function and provides marketable products (Garrity et al. 2010).

All alternative approaches to agricultural intensification based on increasing chemical inputs and uniformity of production systems involve increased use of agricultural biodiversity. This increased use takes two forms: (1) the use of different materials adapted to different agronomic practices and reduced inputs, and (2) the use of increased diversity at ecosystem, species and genetic levels (or at landscape, farm and field scales) (PAR/FAO, 2011), i.e. the use of more species, crop varieties, livestock breeds and wild populations. As De Schutter (2010) noted in his report to the UN Secretary General on the role of agroecology in food security, "These approaches involve the maintenance or introduction of agricultural biodiversity (diversity of crops, livestock, agroforestry, fish, pollinators, insects, soil biota and other components that occur in and around production systems) to achieve the desired results in sustainability and productivity." It has been estimated that traditional agricultural landscapes that are complex and rich in agricultural biodiversity still provide as much as 20% of the

Box 7: Home gardens

Home gardens are estimated to support nearly 1 billion people in the tropics and contain remarkable diversity of food and other utilitarian species – up to a hundred or more species per garden – and offer great potential for improving household food security and alleviating micronutrient deficiencies (Heywood 2013). Efforts to promote nutritious biodiversity through home gardens have been the target of food security and nutrition interventions in many countries (Nielsen et al. 2013; Pudasaini et al. 2013), and may also provide animal products such as chickens, eggs and livestock as in the case of the homestead gardens promoted by Helen Keller International. Some studies have found that a child's nutritional status is associated with the presence of a home garden and that the garden's biodiversity, rather than its size, is the most important factor (Jones et al. 2005). In addition to enhancing food security and nutrition, the presence of home gardens in highly populated areas creates a pleasant and aesthetically pleasing environment, which may have broader health benefits, including mental health benefits, as well (Pushpakumara et al. 2012).

world's food supply (Heywood 2013). This may be a significant underestimate given that it has also been estimated that small-scale producers produce most of the world's food (Pretty and Barucha 2014).

4.2 Global food security, biodiversity and human health

With the growing demand of an expected 9 billion people by 2050, the world still faces tremendous challenges in securing adequate food that is healthy, safe and of high nutritional quality for all, and doing so in an equitable and environmentally sustainable manner (Pinstrup-Andersen 2009; Godfray et al. 2010; Tilman et al. 2011; Foley et al. 2011). Climate change, ecosystems and biodiversity under stress, increasing urbanization, social conflict and extreme poverty all make attaining this challenge difficult.

Despite progress in feeding a growing population, we still live in a world with a highly dysfunctional, and inequitable, food system, where there has been a failure to achieve global food security, in which we have been unable to feed a significant part of humanity adequately, and which continues to contribute to environmental and health problems, high species extinction rates, loss of genetic diversity, and land and ecosystem degradation (Rosin et al. 2012). One major issue is the apparent continuing lack of political will and moral imperative (Horrigan et al. 2002). This is reflected in such continuing problems as the scale of food waste. Of the total food produced, about 30% is lost through post-harvest losses on farms or in the process of marketing, distribution and consumption (Lundqvist 2008). There is clearly significant potential to improve the availability of food and reduce hunger through reducing these losses. In addition to the continued problems of hunger, micronutrient deficiencies undermine the growth and development, health and productivity of over 2 billion people (Micronutrient Initiative 2009). At the same time, according to recent estimates, over 2 billion people worldwide are overweight or obese (Ng et al. 2014).

We face a major global problem associated with the replacement of foods derived from biodiversity with high nutritional significance by globally marketed foods that are higher in energy but less dense in nutrients and other functional factors that often confer some degree of protection against disease. The result is an emerging "double burden"[5] of malnutrition and "hidden hunger"[6] in developing countries. Up to half a million vitamin A-deficient children go blind every year, half of them dying within a year of losing their sight; and iron deficiency is damaging the mental development of 40–60% of children in developing countries. The estimated cost of undernutrition to potential economic development is between US$ 20 and 30 billion annually (Shetty 2010, see also Chapter on nutrition within this volume).[7]

The Declaration of the World Summit on Food Security (FAO 2009) addresses the issue of investments in agriculture highlighting that efforts should focus more on sustainability by supporting sustainable agricultural production and practices aimed at conservation and improved use of the natural resource base and protection of the environment and enhanced use of ecosystem services. Some of the key aspects of improving food security identified by the World Food Summit where agricultural biodiversity is relevant are listed in Box 8 (FAO/PAR, 2011).

4.2.1 Climate change, food security and human health

FAO estimates that food production over the next 40 years will need to increase by about 70% in order to cope with increasing population and dietary demands for more animal-sourced foods. Over the same time frame, climate change is expected to cause significant reductions in not only crop

[5] The Double burden of undernutrition and overnutrition.

[6] Hidden hunger – a lack of essential vitamins and minerals often results in "hidden hunger" where the signs of malnutrition and hunger are less visible in the immediate sense. See also chapter on nutrition in this volume.

[7] Shetty P. (2010) The challenge of improving nutrition: fact and figures. SciDevNet. http://www.scidev.net/en/health/the-challenge-of-improving-nutrition/features/the-challenge-of-improving-nutrition-facts-and-figures-1.html

Box 8. Key aspects of improving food security identified by the World Food Summit Declaration which particularly involve agricultural biodiversity

- Increase production including through access to improved seed and inputs; reduce pre- and post-harvest losses; pay special attention to smallholders.
- Implement sustainable practices, including responsible fisheries, improved resource use, protection of the environment, conservation of the natural resource base and enhanced use of ecosystem services.
- Ensure better management of the biodiversity associated with food and agriculture; support the conservation of and access to genetic resources, and fair and equitable sharing of the benefits arising from their use.
- Recognize that increasing agricultural productivity is the main way to meet the increasing demand for food, given the constraints on expanding the amount of land and water used for food production.
- Mobilize the resources needed to increase productivity, including research, and the review, approval and adoption of biotechnology and other new technologies.
- Enable all farmers, particularly women and smallholder farmers from countries most vulnerable to climate change, to adapt to, and mitigate the impact of, climate change.
- Support national, regional and international programmes that contribute to improved food safety and animal and plant health.
- Encourage the consumption of foods, particularly those available locally, which contribute to diversified and balanced diets.
- Address the challenges and opportunities posed by biofuels.

Reference: FAO/PAR 2011

production but also the nutritional content of foods, particularly in respect of production of C3 grains and legumes, which provide a large portion of the global population with their primary source of iron and zinc. Increasing CO^2 levels will lead to reductions ranging between 5% and 10% in the iron and zinc content of the edible portion of these crops, possibly increasing the burden of disease for these deficiencies that already cause a loss of 63 million life-years annually (Myers et al. 2014). Climate change is also expected to impact heavily on fish and livestock resources. Livestock in particular will be impacted, especially in arid and semi-arid regions, including effects on pasture species composition and forage quality. Further, increasingly frequent and severe pest and disease attacks are expected. Bebber et al. (2013) highlight poleward movements of pests and pathogens to new areas from 1960 onwards. While soil-borne pathogens and diseases are likely to be more of a problem under increasing temperatures (Jaggard et al. 2010), Tirado et al. (2010) and Lake et al. (2012) also highlight the likelihood of climate change impacts on food contamination and foodborne diseases through the increased incidence of existing pathogens or the emergence of new pathogens. The Fifth Assessment Report of the Intergovernmental Panel on Climate Change[8] concluded that climate change is affecting all aspects of food security and agriculture, and that impacts on crop yields are already evident across several regions of the world.

Agricultural biodiversity, including utilization, and maintenance of plant genetic resources for crop improvement and diversification, is an important strategy in dealing with ongoing climate change and food security (FAO 2015). In addition to their nutritional potential, Foley et al. (2011) highlight important opportunities to improve crop yield and resilience, by improving the myriad neglected and underutilized species and conserving crop diversity as well as crop wild relatives. Bambara groundnut (*Vigna subterranea*) is well known for its drought tolerance and ability to grow in harsh and marginal environments, as are a number of minor millets commonly grown in South Asia. Ca˜nihua (*Chenopodium pallidicaule*), an underutilized Andean grain, has significant frost tolerance, while the perennial seabuckthorn (*Hippophaerhamnoides*) has considerable tolerance to abiotic stresses like frost and cold, assumed to be associated with the high levels of ascorbic acid and *myo*-inositol it contains (Padulosi et al. 2011; Yadav et al. 2015).

Crop wild relatives represent one of our most precious resources in trying to deal with climate change, while at the same time improving the nutritional quality of crops and food (Hunter and Heywood 2011). As well as containing genetic traits for enhanced nutritional quality, they also have novel pest resistance and tolerance to heat, drought and salinity, among other traits (Godfray et al. 2010; Hunter and Heywood 2011; Hodgkin and Bordoni 2012). Crop wild relatives have already provided many useful genes for crop improvement, which have been introduced to improve varieties through conventional breeding techniques in crops as diverse as wheat, potato, tomato and lettuce (Hajjar and Hodgkin, 2007). However, crop wild relatives, as well as other genetic diversity, cannot be taken for granted and they are currently under threat from changing climate (Jarvis et al. 2008; Lira et al. 2008; Hunter and Heywood, 2011).

Negative impacts on crop yields or when crops fail as a result of climate change may mean a greater role for wild food species for food security and nutrition in the future. Yet climate change is also likely to negatively impact on wild edible species themselves. A recent study (Carr et al. 2013) of wild plant and animal species of the Albertine Rift region of East and Central Africa combined climate change vulnerability and use assessments to identify those species utilized by communities

Box 9. Agro-ecological resilience after Hurricane Mitch in Nicaragua

In October 1998, Hurricane Mitch hit Central America, causing damage worth at least US$ 6.7 billion. Over 10000 people died and 3 million were displaced or left homeless. In Nicaragua, a comparative study was carried out using participatory approaches, which involved farmers and local NGOs, on the levels of resistance to the hurricane of "sustainable" farms using a variety of sustainable land management practices, and neighbouring "conventional" farms that lacked those practices. On average, agro-ecological plots on sustainable farms had more topsoil, higher field moisture, less erosion and lower economic losses after the hurricane than the plots on conventional farms. The differences in favour of agro-ecological plots tended to increase with increasing levels of storm intensity, increasing slope and years under agro-ecological practices, though the patterns of resistance suggested complex interactions and thresholds.

(Holt-Gimenez 2002. See also the Chapter on disaster risk reduction in this volume)

[8] http://www.ipcc.ch/report/ar5/

most likely to be negatively impacted by climate change. The study found that 14 amphibians (13% of those assessed), 17 birds (2%), 19 freshwater fish (3%), 24 mammals (7%), 33 plants (36%) and 25 reptiles (15%) of known importance for use, including food, were among those at greatest vulnerability to climate change impacts. For these reasons, better knowledge of how wild food species are likely to be impacted by climate change will be critical for both biodiversity conservation and developing sustainable use and livelihood strategies.

More biodiversity-friendly crop and food production mitigation strategies that might contribute to reduced methane and nitrous oxide emissions could include improved soil management practices, such as the enhanced use of mulching, cover cropping, conservation agriculture, more efficient N utilization, as well as improved rice cultivation and manure management practices (Reynolds and Ortiz 2010; Cribb 2010). Among other things, such strategies will require new crop varieties, including breeding of varieties with reduced carbon dioxide and nitrous oxide emissions, different crop combinations, and modified management systems and agronomic practices (Hodgkin and Bordoni 2012; Reynolds and Ortiz 2010).

5. Conclusions

The increase in food production achieved over the past decades has been accompanied by significant losses in agricultural biodiversity, as production systems (crop and animal) have become more uniform and dependent on externally derived chemical inputs. The loss of agricultural biodiversity has been associated with reductions in ecosystem service provision, often accompanied by negative impacts on human health. It is clear that agricultural biodiversity can make significant contributions to improving food security, nutrition and human health, and will play an essential role in achieving sustainable food production and improving the productivity needed to meet the challenges of climate change. The chapter points to a number of areas of work that can help to improve the contribution of agricultural biodiversity to food security and human health. These are listed below:

1. There are still significant knowledge gaps in relation to the optimum use and deployment of agricultural biodiversity in production systems. The ways in which agricultural biodiversity can improve ecosystem-regulating and-supporting services is still poorly understood in terms of how to achieve real benefits in different production systems. This will involve a substantial programme of integrated transdisciplinary research, which fully involves producers, and links the production of improved crop and livestock materials to the adoption of agronomic practices that support biological functions in production systems.

2. The importance of diversity-rich production systems and diversification is widely recognized in respect of their contribution to food security, sustainability, adaptation to change and human health. However, the ways in which such approaches can be adopted with direct benefits to producers who are committed to uniform non-diverse approaches has not been clearly established. This will involve taking account of biological, social, economic and political dimensions, and of recognizing both producer and consumer concerns.

3. Even when practices that provide food security, health and diversity benefits have been identified (such as alternatives to the use of pesticides or of reducing the pollination deficit through improved pollinator diversity), there remain economic, policy and other barriers to the adoption of such practices, especially at the national level. These need to be identified and alternatives adopted. It will be especially important to investigate ways in which the full economic value of the use of agricultural biodiversity can be measured and rewarded.

4. A number of international policies and instruments have been developed to take account of the importance of agricultural biodiversity. However, there remain significant challenges in achieving full recognition of its importance in, for

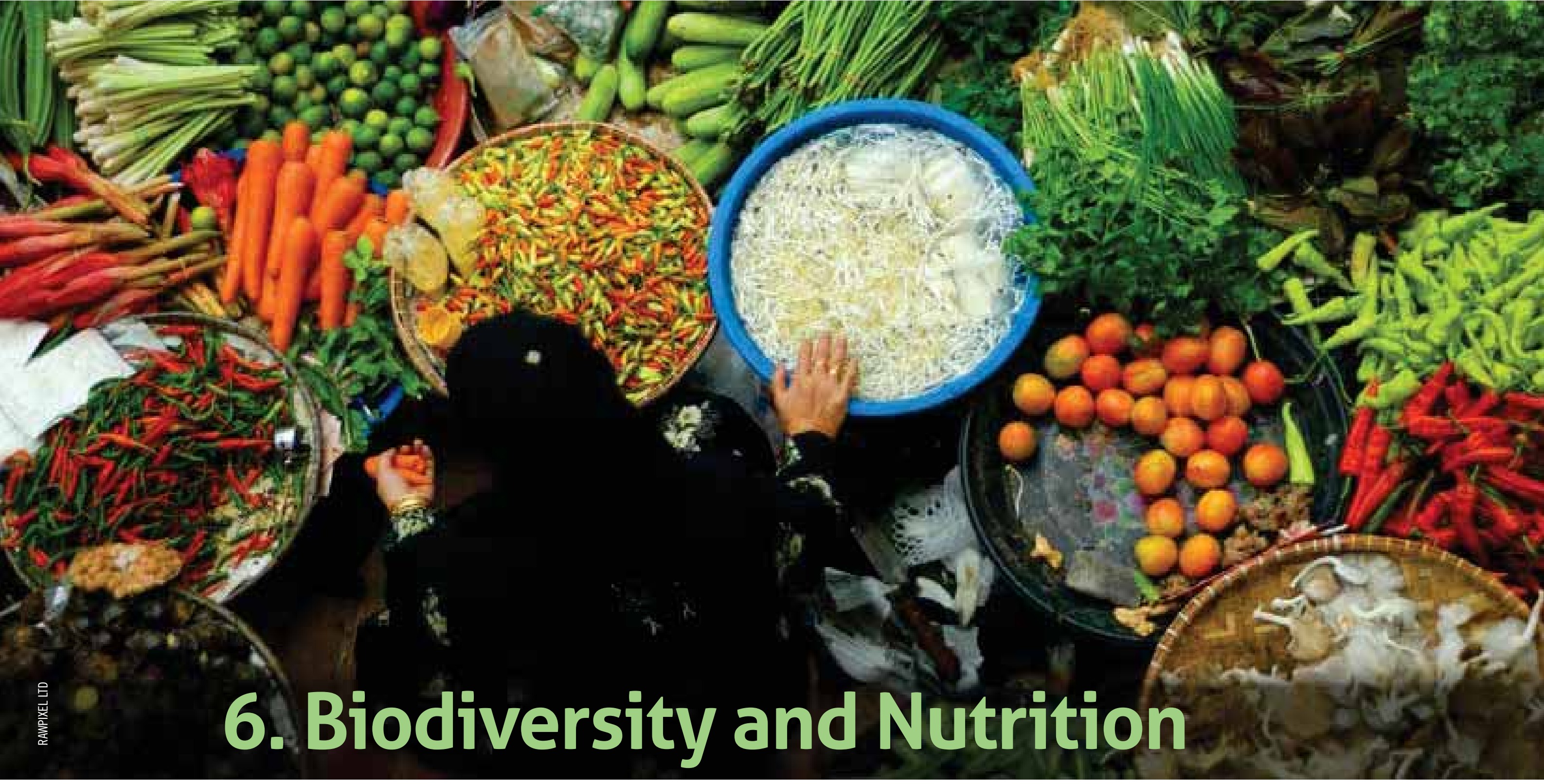
example, climate change adaptation agendas[9] and the global food security debates of the Committee on World Food Security (CFS). A key objective of international policy efforts should be to ensure the enhanced availability of agricultural biodiversity to users.

5. Sustainable development goals and targets, and the post-2015 Development Agenda provide an important global entry point to better recognition of the ways in which agricultural biodiversity and health co-benefits can be maximized. The goals of ending hunger, malnutrition, increasing agricultural productivity and incomes, ensuring sustainable and resilient food production systems, and maintaining genetic diversity provide a framework for developing a compelling agenda on the value of the improved use of agricultural biodiversity.

6. The growing concerns of consumers about food production approaches and the demand for environmentally friendly approaches that provide adequate rewards for rural communities and safe food provide important entry points for exploring the contributions that agricultural biodiversity can make to these wider social objectives.


BIOVERSITY INTERNATIONAL

[9] The recent adoption of guidelines on the integration of genetic diversity in climate change adaptation planning by the FAO Commission on Genetic Resources for Food and Agriculture is a beneficial development.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6. Biodiversity and Nutrition

1. Introduction

Malnutrition remains one of the greatest global health challenges we face and women and children are its most visible and vulnerable victims. Agricultural production is theoretically able to feed the world's population in terms of calories (FAOSTAT, 2014), yet it is estimated that half the world's population still suffers from one or more forms of malnutrition. In all its forms, malnutrition is closely linked to disease – as both a cause and effect – and it is the single largest contributor to the global burden of disease (WHO 2012a).

Countries are increasingly facing complex multiple burdens of malnutrition, with undernutrition and micronutrient deficiencies coexisting with overweight and obesity in many parts of the world, often even within the same population or family (Shrimpton 2013). Based on data released in 2014, 161 million children under the age of five are estimated to be stunted, almost 1.5 billion people are estimated to be overweight, over 600 million to be obese (Ng et al. 2014) and two billion are estimated to be deficient in one or more micronutrients, a phenomenon referred to by some as "hidden hunger". These conditions all have severe consequences for survival, for morbidity, and for the ability of individuals, the economy and society to thrive (IFPRI 2014). Nutrient deficiencies alone can lead to several global health and development challenges, impaired intellectual and psychomotor development, reduced physical growth, and a range of other problems. It has also been found to increase morbidity from infectious diseases in infants and young children (see Muthayya et al. 2013 and references therein).

In recent years, the direct and indirect dependence and impact of human nutrition on biodiversity has been increasingly acknowledged by the health (WHO 2012b; UN SCN 2013 and ICN2), agriculture (FAO 2013a) and environment sectors (UNEP 2012; CBD 2014). These activities have included landmark research efforts, innovative development programmes and projects, policy initiatives, and advocacy campaigns.

Biodiversity is a key source of food diversity and provides a natural richness of nutrients (macronutrients such as carbohydrates, proteins and fats, and micronutrients [vitamins and minerals] and bioactive non-nutrients for healthy human diets (Blasbalg et al. 2011; Fanzo et al. 2013). In addition, biodiversity also underpins critical supporting ecosystem services, such as pollination and soil fertility, essential to food production, both in terms of quantity and quality.

In the field of nutrition, food is seldom dealt with independently of the nutrients it contains, the whole diet of which it is a part and the ecosystems it is derived from. Taking a whole diet approach enables the use of different combinations of diverse foods, and their many interactions, to improve dietary quality and meet nutritional needs. It also takes into account local knowledge – threatened in many parts of the world (Sujarwo et al. 2014) – and cultural acceptability and culinary traditions.

Biodiversity for human nutrition therefore includes the diversity of plants, animals and other organisms used in food systems, covering the genetic resources within and between species, and provided by ecosystems. In nutrition science, however, the diversity of diets covers mostly the inter-species biodiversity, and the intra-species biodiversity is a still underexplored dimension from a nutritional perspective.

Despite the increased recognition of the potential of biodiversity for nutrition, national global food supplies have become more homogeneous in composition, being largely dependent on a few global crops (Khoury et al. 2014).

Agricultural programmes and policies often focus on increasing the production of a few staple crops, and their success is measured in terms of the food quantity or dietary energy supply. Ample quantity does not necessarily ensure appropriate nutritional quality, with staple crops unable to provide the diversity and adequate amounts of nutrients to meet human requirements, especially much-needed micronutrients. This has led to numerous calls demanding new approaches to agriculture for improved nutrition outcomes, often referred to as "nutrition-sensitive agriculture" (Ag2Nut CoP, 2013; Turner et al, 2103; McDermott et al. 2015).

Notwithstanding the productivity successes achieved in the agricultural sector in the past several decades, it is becoming increasingly clear that current methods and levels of food production and consumption are not sustainable, (FAO 2013b) and that finite natural resources and genetic diversity are being corroded or lost in the process. A reduction in biodiversity is a prime example (Toledo and Burlingame 2006; Wahlqvist and Specht 1998).

GRAPH 1: Global malnutrition

At the time of going to press the global figure of the number of people undernourished globally was estimated at 795 million (SOFI 2015) http://www.fao.org/3/a-i4646e.pdf

In view of these trends, monitoring and ensuring biological diversity in global food systems for nutrition and other outcomes is increasingly important and intimately tied to the underlying objectives of the post-2015 Development Agenda (see also Section 11 in this chapter as well as Part III chapters in this volume).

This chapter provides an overview of our knowledge on food composition and the diversity of food production systems. It also examines the contribution of wild foods and traditional food systems and cultures to dietary diversity and nutrition as well as the rising trend known as nutrition transition and Noncommunicable diseases (NCDs). The chapter will further discuss examples of initiatives for biodiversity and nutrition, including in the context of urbanization. Finally, relevant global policy initiatives and future directions relevant to the post-2015 Development Agenda are explored.

2. Biodiversity and food composition

Food composition, i.e. the analysis of nutrients and other bioactive components in food, was traditionally the domain of the agriculture sector, with FAO taking an early leadership role as early as the 1950s, and the US Department of Agriculture developing the single largest national food composition database. In recent decades, the health and nutrition sectors have become the main users of food composition data in studies exploring the relationship between nutrient or dietary intake and diseases.

Given the inherent difficulties in collecting information about people's diets, many national dietary surveys have recorded food intake at a very aggregated level, sometimes using the common name of the species (e.g. spinach) without specifying genetic variety, sometimes as a food type without specifying species (e.g. leafy greens), and sometimes simply as a broad category with no indication of the food itself (e.g. vegetable).

The goal of food composition to date has been to provide nutrient data at that same aggregate level, and strive for "year-round, nation-wide mean values", with all compositional differences related to agro-ecological zone, seasonality and, most significantly, biodiversity being obscured. This has been the lamentable trend, despite knowledge among food composition professionals that nutrient content differences among varieties of the same species can be greater than the differences between species.

The scientific literature reports significant intraspecific differences in the nutrient content of most plant-source foods (FAO/INFOODS, 2013a). Significant nutrient content differences in meat and milk among different breeds of the same animal species have also been documented (Medhammar et al. 2012; Barnes et al. 2012; Hoffmann and Baumung 2013). The differences are statistically significant, and more importantly, nutritionally significant, with 1000 and more-fold differences documented. For example, consumption of 200 g of rice per day can represent less than 25% or more than 65% of the recommended daily intake (RDI) of protein, depending on the variety consumed (Kennedy and Burlingame 2003). One apricot variety can provide less than 1% or more than 200% of the RDI for vitamin A. Variety-specific differences can represent the difference between nutrient deficiencies and nutrient adequacy in populations and individuals (Lutaladio et al. 2010).

Many countries, such as Bangladesh with its diversity of inland water bodies and ecosystems, are rich in fish biodiversity (see Box 2 of the agricultural biodiversity chapter). Freshwater aquaculture is also rapidly growing with many households now having access to a pond. Fish, especially small indigenous species, are an irreplaceable rich source of food in the diets of millions. They contain essential, highly bioavailable nutrients, including high-quality protein, essential fatty acids and micronutrients. Some, such as hilsa (*Tenualosa ilisha*), have a high fat content and high levels of polyunsaturated fatty acids. Common small indigenous species such as mola (*Amblypharyngodon mola*), chanda (*Parambassis baculis*), dhela (*Rohtee cotio*) and darkina (*Esomus danricus*) also have a high content of vitamin

A as the eyes and gut are consumed. Because many small indigenous species are eaten whole, including bones and head, they can also represent a very rich source of highly bioavailable calcium, along with high iron and zinc content. The edible parts of larger cultured fish such as silver carp (*Hypophthalmichthys molitrix*), tilapia (*Oreochromis niloticus*) and panga (*Pterogymnus laniarius*) do not contain vitamin A, iron or zinc, and as the bones of large fish are discarded as plate waste, they do not contribute to calcium intake (Thilsted 2013).

Several studies illustrate well the importance of understanding the nutrient composition of biodiversity. For example, in the latter part of the twentieth century, vitamin A deficiency was identified as a serious public health problem among many Pacific Island nations, with over 50% of children manifesting stunting, night blindness, Bitot spots, xerophthalmia causing blindness, and severe repeated respiratory infections (see Box 6). Despite the fact that this was attributed to decreased consumption of traditional, local vitamin A-rich foods, interventions promoted since the 1980s were fortification of margarine and distribution of vitamin A capsules (Schaumberg et al. 1995). Food composition research in the Pacific later revealed that local varieties of familiar species were often superior in their nutrient content to the commonly consumed varieties that dominated the marketplace (Englberger and Johnson 2013, Table 1).

In a study by Huang and co-workers (1999), the nutrient content of different variety of sweet potato was analysed, showing dramatic variety-specific differences, with high-carotenoid varieties containing 65 times more β-carotene than the low-carotenoid varieties. The pro-vitamin A carotenoid content of some local banana varieties was more than 8000 μg per 100 g, compared to the common Cavendish variety with about 25 micrograms per 100 grams (Englberger et al. 2003a, b). After the publication of data on the nutrient richness of local foods in Pacific Island countries (see Table 1), it was clear that agricultural biodiversity could provide more sustainable and culturally acceptable solutions to several of the problems of malnutrition in the region (Englberger et al. 2003a, 2003b, 2003c, 2006, 2008, 2009; Kuhnlein et al. 2009, 2013; Burlingame and Toledo 2006; Rubiang-Yalambing et al. 2014). As more and better data become available, food biodiversity, covering thousands of varieties of fruits, vegetables, grains and legumes, animal species and breeds, edible insects and fungi, is being recognized for its high nutritional value and great potential for improving the nutritional status of local communities. Furthermore, many varieties of aibika (Abelmoschus manihot L.) are consumed in the Pacific region as a common leafy vegetable particularly in Papua New Guinea (PNG) where a recent study (Rubiang-Yalumbing et al. 2014) has highlighted its high nutritional value and potential for improving the nutritional status of local communities. This study has also highlighted genotype and environment interactions that significantly influence the micronutrient concentrations of even the same accessions from year to year, even when planted in the same area.

The selective specialization in a smaller number of crops and crop genotypes has made some crops less resilient to diseases and has limited the range of available nutrients. Decades of research shows that while yields of staple crops such as maize, wheat and rice are increasing, their nutritional contents tend to be decreasing (Jarrell and Beverly 1981; Simmonds, 1995). Moreover, as highlighted in the chapters on agricultural biodiversity and climate change in this volume, climate change may significantly influence biodiversity resources, food production and food contamination, including the incidence of aflatoxins, with implications for food security, diets and nutrition (Cotty and Jaime-Garcia 2007; Tirado et al. 2013). Climate change is also expected to cause significant reductions in the nutritional content of certain foods, particularly C3 grains and legumes, which provide a large portion of the global population with their primary source of iron and zinc. Increasing CO_2 concentrations may lead to reductions ranging between 5% and 10% in the iron and zinc content of the edible portion of these crops (Myers et al. 2014).

Table 1: Carotenoid content of selected traditional staple food varieties compared to rice (μg/100 g edible portion) in Pohnpei, FSM

Variety	Species	Flesh colour[1]	β-carotene	α-carotene	β-crypto-xanthin	β-carotene equivalents[2]	RE[3]	RAE[4]	Total carotenoids[5]
Banana									
Utin lap	*Musa spp*	Orange: 15	8508	na	na	8508	1418	709	na
Karat	*Musa spp*	Yellow/orange: 8	2230	455	30	2473	412	206	4320
Giant swamp taro									
Mwahng Tekatek Weitahta	*Cyrtosperma merkusii*	Yellow: 1	4486	na	na	4486	748	374	na
Mwahngin Wel	*Cyrtosperma merkusii*	Yellow: 4	2930	2040	120	4010	668	334	5630
Breadfruit									
Mei Kole	*Artocarpus mariannensis*	Yellow	868	142		939	132	78	na
Pandanus									
Luarmwe	*Pandanus tectorius*	Yellow	310	50	20	345	58	29	5200
Imported food									
Rice, white or brown	*Oryza sativa*	White	na	na	na	0	0	0	0

na- not analysed * below detection limits

Notes: Analyses were conducted at different laboratories, see published papers. All used state-of-the art techniques, including high performance liquid chromatography (HPLC). Samples were as eaten: raw ripe (banana, pandanus); cooked ripe (breadfruit) and cooked as mature (taro). All samples were composite samples: 3–6 fruits or corms per sample, collected from Pohnpei State, Federated States of Micronesia. Data are from: Englberger et al. 2009a (pandanus), Englberger et al. 2008 (giant swamp taro), Englberger et al. 2006 (banana), Englberger et al. 2003a (breadfruit). Imported food: rice: Dignan et al. 2004. Imported rice has now become a common staple food in Pohnpei.

[1] Raw flesh color was described visually and estimated using the DSM Yolk Color Fan, numbers ranging from 1 to 15 for increasing coloration of yellow and orange.

[2] β-carotene equivalents: content of β-carotene plus half of α-carotene and β-cryptoxanthin.

[3] Retinol equivalents (conversion factor 6:1 from β-carotene equivalents to RE).

The estimated recommended dietary intake (RDI) for a non-pregnant, non-lactating female is 500 μg RE/day and for a child 1–3 years old is 400 μg/day (FAO/WHO 2002).

[4] Retinol activity equivalents (conversion factor 12:1 from β-carotene equivalents to RAE)

[5] This includes estimates of identified and unidentified carotenoids level but is unrelated to vitamin A content.

Source: Englberger and Johnson, 2013

Food composition and food consumption indicators for biodiversity (see Box 1) can help track the extent to which food biodiversity is being documented for the purposes of human nutrition. While progress is being made in this area and more data on the nutrient composition of food biodiversity are required, enough evidence exists to warrant actions to provide biodiversity-based solutions to solve some of the persistent problems of malnutrition (Burlingame et al. 2009).

3. Systems diversity and human nutrition

A shared axiom of ecology and nutrition is that diversity enhances the health and function of complex biological systems (DeClerck et al. 2011; DeClerck 2013; Khoury 2014).

A diverse diet should contain many different foods consumed in sufficient amounts. A healthy human diet is composed of many hundreds of beneficial bioactive components, a small subset of which have been characterized and identified as nutrients. A varied diet is the only way to ensure adequate

Box 1. Food composition and food consumption indicators for biodiversity

Specific indicators for biodiversity are needed to understand, quantify, and monitor the role of biodiversity in human diets, and the impact of biodiversity-related nutrition interventions and initiatives. Among relevant activities under the Cross-cutting Initiative and within the framework of the Biodiversity Indicator Partnership, FAO, INFOODS and Bioversity International convened a series of meetings and expert consultations to propose, develop and monitor nutrition indicators for biodiversity.

During two technical meetings, two nutrition indicators were developed: Indicator 1 on food composition (FAO, 2008) and Indicator 2 on food consumption (FAO 2010).

Indicator 1 relates to the availability of compositional data, i.e. nutrients, bioactive non-nutrients, and contaminants, on foods meeting the criteria of biodiversity. The criteria include food items reported at the taxonomic level below the species level, along with wild, neglected and underutilized species. In 2008, the baseline report counted 5519 foods for Indicator 1. In subsequent years, between 835 and 5186 foods were added annually (FAO/INFOODS 2013). Researchers worldwide are submitting their data to the FAO/INFOODS Food Composition Database for Biodiversity (FAO/INFOODS 2013a), which serves as an international repository of analytical data on biodiversity of sufficient quality. These data are freely available, widely disseminated, and frequently cited.

Indicator 2 refers to a count of the number of biodiverse foods reported in food consumption or similar surveys (FAO 2010). In 2009, the baseline report counted 3,119 foods. In the two reporting periods that followed, 1,827 and 1,375 foods were added. A secondary survey indicator was developed as a count of the number of food consumption and similar surveys taking biodiversity into consideration in their design and/or reporting, with at least one reported food meeting the criteria for Indicator 2 (FAO/INFOODS 2013).

These indicators have proven useful in stimulating the collection and dissemination of biodiversity data for food composition and consumption. They are also advocacy tools to policy-makers and programme managers for effectively raising awareness of the importance of biodiversity for nutrition and providing documentation of the ever-increasing knowledge of biodiversity and human nutrition.

Reference: http://www.fao.org/infoods/infoods/food-biodiversity/it/ (accessed 5 March 2015) intakes of these nutrients and related compounds. Researchers use different methods to determine the adequacy of diets of individuals, households and communities, including the simple and easy to administer Diet Diversity Score (DDS), which is defined as the number of food groups consumed by an individual or family over a certain time period, mostly 24-hours. Many studies carried out among different age groups show that an increase in individual DDS is related to increased nutrient adequacy, health and micronutrient density of diets of non-breastfed children, adolescents and adults (Hatloy et al. 1998; Ruel et al. 2004; Steyn et al. 2006; Kennedy et al. 2007; Mirmiran et al. 2004; Foote et al. 2004; Lobstein et al. 2015 and references therein; Arimond and Ruel 2004; Kant et al. 1993; Slattery et al. 1997; Levi et al. 1998) and food security (Ruel 2003).

Similarly, in ecology, species diversity has been shown to stimulate productivity, stability, ecosystem services, and resilience in natural (Cadotte et al. 2012; Gamfeldt et al. 2013; Hooper et al. 2005; Zhang et al. 2013; Hooper et al. 2012) and agricultural ecosystems (Kremen and Miles 2012; Davis et al. 2012; Kirwan et al. 2007; Picasso et al. 2008; Bonin and Tracy 2012; Mijatovic et al. 2013; Hajjar et al. 2008).

Community ecology has demonstrated that increases in biodiversity can lead to increases in plant community productivity when species complement each other, or use resources differently. Many studies of biodiversity and ecosystem function have demonstrated that there is much variance that cannot be explained by species richness (DeClerck et al. 2011). For example, does it matter that an ecosystem has five species, or would it be more important that a system has five different functional groups? Is a field with maize, rice, wheat, sorghum, and millet the equivalent of a field with maize, beans, squash, sweet potato and guava? Both have five species, but the latter contains five functional distinct species from a nutritional point of view in contrast to the former where all of the species are from the grass family, high in carbohydrates, but poor in essential nutrients.

Though ecologists have focused increasingly on the relationship between biodiversity and ecosystem functioning, there has been little but increasing focus on the capacity or role that ecosystems play in providing the essential elements and nutrients of the human diet, as proposed through the concept of "eco-nutrition" (Deckelbaum et al. 2006; DeClerck et al. 2011). While diet diversity has long been recognized as important for adequate nutrient intake and human health, the concept of nutritional diversity has yet to be integrated into planning, assessments, and policies and programmes of agricultural and food systems.

In the past, food-based interventions have been mostly oriented toward single nutrients (Frison et al. 2006). This may in part be attributed to a lack of knowledge in earlier years of the interactions among nutrients in human physiology and metabolism. From various recommendations for high-protein diets (Brock et al. 1955) and later for high-carbohydrate diets (McLaren 1966; McLaren 1974) to more recent efforts directed at the elimination of micronutrient deficiencies (UN committee on nutrition, 2000; Ruel and Levin 2002), the attention has generally concentrated on single nutrient approaches. The introduction of crops focusing on single-nutrients serves as an important means to address specific nutrients (macro or micronutrients), but caution must be exercised as any single crop, including a fruit or vegetable crop, does not assure the complex nutritional requirements needed to ensure good health (Graham et al. 2007, DeClerck et al. 2011).

Deeper, less obvious, interactions and relationships which affect nutritional outcomes and have long been important in traditional food cultures are at play. The nutritional complementarity of the traditional "American three-sisters" polycultural system, which involves planting maize, beans and squash in the same hole, is a combination that is almost nutritionally complete, with carbohydrates and energy provided by maize, protein by beans and vitamin A by squash (DeClerck and Negreros-Castillo 2000; DeClerck 2013). Mayan farmers when eating meals comprising these plants do so with condiments prepared with lime juice, which is very important in making the niacin present in the beans bioavailable. So much so in fact, that when maize was introduced outside of Latin America without the accompaniment of beans or lime, these dietary interactions were lost leading to negative nutritional outcomes including pellagra (DeClerck 2013). Dietary interactions such as these are often overlooked but play a major role in improving the bioavailability of certain minerals (see Box 2).

A recent methodology applies ecological diversity to nutritional traits, resulting in a metric coined nutritional functional diversity or Nut FD (Figure 1; DeClerck et al. 2011; Remans et al. 2011). Household, landscape and national-level assessments (DeClerck et al. 2011; Remans et al. 2011; Jones et al. 2014; Remans et al. 2014) illustrate the importance of such diversity in local and national food systems for dietary diversity and key nutrition health outcomes. Thereby these studies offer a potential intermediate indicator in the biodiversity–nutrition nexus that environment, agriculture and nutrition strategies can consider and monitor towards using a systems approach, not replacing but complementing dietary diversity indicators and agrobiodiversity indicators.

Diversity in production and food systems can impact nutrition not only through the diversity of nutrients made available for human consumption but also through other aspects of the production and food system that influence nutrition-related outcomes more indirectly. Crop plants that depend on pollinators are key sources of vitamin A, C and folic acid, and on-going pollinator decline may exacerbate current challenges of accessing a nutritionally adequate diet (Box 3; see also sub-section on pollination in the agricultural biodiversity chapter). Species diversity has

Box 2. Increasing small fish intake in pregnant and nursing women in rural Bangladesh

In Bangladesh, a fish chutney was developed to increase the contribution of essential nutrients from an animal-source food in the first 1000 days of life, to supplement the diet of pregnant and breastfeeding poor, rural women in Bangladesh, and promote growth and development in infants and young children. The chutney is based on a traditional "achar" or pickle recipe which is commonly served with boiled rice and curry vegetables. The chutney contains 37% dried small fish, 15% oil, 37% onion, 7% garlic and 4% chili. The recommended serving is one heaped tablespoon of fish chutney (equal to 30 g containing 60 g of raw fish), to be eaten with the main meal. The fish chutney is well-liked by women and is a good source of micronutrients such as iron, calcium, zinc and vitamin B12, as well as animal protein and essential fatty acids. The particular relevance of the latter for cognition in the first 1000 days is especially important. In addition, the fish itself enhances the bioavailability of minerals from the plant-source foods (rice and vegetables) in the meal.

The fish chutney, produced by a women's group, is presently being distributed to 150 pregnant and lactating rural women in Sunamganj, north-eastern Bangladesh, through a project aimed at improving the livelihoods of poor rural households. The small fish used is sourced from the wetlands and sun-dried by local women. Assistance, training and supervision have been provided to ensure safe and hygienic conditions for processing, storage and transportation. Women receiving the fish chutney report producing "a lot of milk" and their children "getting more milk, being satisfied and growing well". Partners have shown interest in using the product in national food programmes, emergency response food rations, school feeding programmes and for sale in local and urban outlets.

This project demonstrates that food processing is important for highly perishable products such as fish, fruit or vegetables. They may increase food safety, market opportunities, the geographical and temporal usage, as well as the livelihood of small-scale producers.

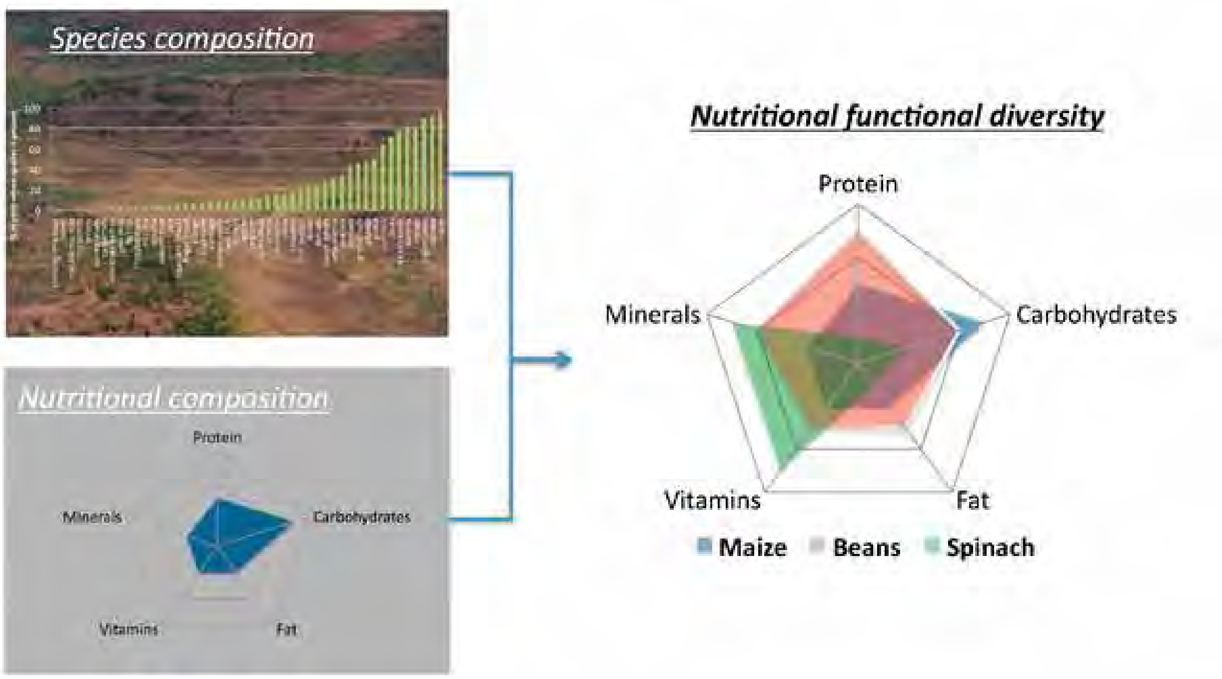
been shown to stimulate productivity, stability, ecosystem services, and resilience in natural and in agricultural ecosystems (Cadotte et al. 2012; Gamfeldt et al. 2013; Zhang et al. 2012; Kremen and Miles 2012; Khoury et al. 2014). In general, increasing the number of species in a community or system will enhance the number of functions provided by that community, and will reinforce the stability of provision of those functions (DeClerck et al. 2011).

By using diversity metrics in agriculture–nutrition strategies, synergies as well as trade-offs with other outcomes, e.g. environmental benefits, can be evaluated and taken into account. In view of global national food supplies that have become more homogeneous in composition (Khoury et al. 2014), monitoring and ensuring diversity for nutrition and other outcomes seems increasingly important.

A CGIAR initiative, nutrition-sensitive landscapes (NSL), applies such systems approaches to concrete low-income settings. The NSL initiative is about setting nutritional, environmental and agricultural targets together, and identifying mechanisms to achieve these using a systems approach. The overall objective is to create synergies and minimize trade-offs between reducing malnutrition of vulnerable populations and restoring and employing ecosystem services. NSL does not imply that the environment can produce all the nutrients required for adequate human nutrition; it does, however, mean a focus on building biological diversity into the landscape, diet, market and food system to provide multiple sources of nutrients, and contribute to environmental and population resilience. NSL is currently strongly embedded with the farming systems research of the CGIAR in a diversity of settings, from aquatic agricultural systems, to humid tropics and forest areas. Across these diverse settings, biodiversity and dietary diversity sit at the nexus of environment, agriculture and nutrition, and serve as the entry point for this landscape-based approach.

FIGURE 1: Schematic presentation of the nutritional functional diversity metric, based on (1) species composition in a given farm or landscape and (2) nutritional composition of these species. Thereby the nutritional FD metric provides a way to assess complementarity between species for their nutritional function. **B:** Nutritional functional diversity plotted against species richness for 170 farms in three Millennium Villages project sites, Sauri in Kenya, Ruhiira in Uganda and Mwandama in Malawi.

A) B)



Source: Remans and Smukler 2013

"Landscape approaches" have gained prominence in the search for solutions to reconcile multiple objectives, particularly in the field of conservation and development trade-offs (Sayer 2009). In general, "landscape approaches" seek to provide tools and concepts for allocating and managing land to achieve social, economic, and environmental objectives in areas where agriculture, mining, and other productive land uses compete with environmental and biodiversity goals (Sayer et al. 2013). In NSL, "landscape" refers, it is referred to the spatial extent that influences both nutrition and the environment in the study areas, including socioeconomic features such as locations of markets and transportation networks, and biophysical features such as watersheds. Households and farming systems in rural areas, especially in low-income settings, are often strongly dependent on resources available in the landscape. In the social-institutional domain, households and communities continuously interact with each other and with markets, political and social institutions. These interactions have a strong influence on household functioning and food provisioning. Combining multi-objective modelling and participatory research, NSL searches for and tests potential synergies between improving availability, access and demand for a diversity of nutritious foods and managing ecosystem services.

Box 3. Pollinator declines, human nutrition and health

Declines in animal pollinators are a subset of biodiversity loss that have been well documented around the globe (Vanbergen 2013; Burke et al. 2013; Potts et al. 2013). Over the past decade, the human health implications of these declines have received increasing attention. Pollinators are estimated to be responsible for roughly one third of human caloric intake (Kleine et al. 2007) as well as up to 40% of the global nutrient supply (Eilers et al. 2011). Regions where pollinators contribute most heavily to nutrient production may also be those where human populations are suffering from the largest burdens of micronutrient deficiency diseases (Chaplin-Kramer et al. 2014). In the first published analysis of human vulnerability to pollinator declines based on an evaluation of population-level dietary patterns, Ellis et al. (2015) found that as much as 56% of a population could be placed at new risk of vitamin A deficiency as a result of the loss of animal pollinators.

Perhaps even more significant in terms of global health is the potential impact of pollinator declines on the yields of food groups whose intakes, as a whole, have recently been shown to have very large impacts on the global burden of disease. If pollinators' work would need to be done manually by mankind, additional economic costs would appear for a work less efficiently performed. The recent assessment of the global burden of disease has emphasized a global pandemic of NCDs including cardiovascular diseases, diabetes, and diet-related cancers (Lim et al. 2010). Because their intakes reduce the risk of these diseases, low intakes of fruit, nuts and seeds, and vegetables have been shown to rank fourth, twelfth, and seventeenth on the list of global risk factors for burden of disease. Yields of each of these food groups are highly pollinator dependent. A recent analysis involving a member of our authorship group is currently in press at the Lancet and suggests very large global burdens of disease would result from reduced intake of these food groups as a consequence of animal pollinator declines. This analysis also emphasizes that large numbers of people around the world would additionally be placed at risk for folate and vitamin A deficiency, and many who are already deficient would become more deficient. Thus, animal pollinator declines could lead to substantial new disease burdens from both micronutrient deficiencies and chronic diseases.

4. Wild foods and human nutrition

3.1 Wild foods and diet diversity

Wild biodiversity has an important role in contributing to food production and security in many agroecosystems worldwide (Scoones et al. 1992; Johns and Maundu 2006; Termote et al. 2011; Turner et al. 2011; Dogan 2012; Termote et al. 2012a; Mavengahama et al. 2013; Vinceti et al. 2013; Powell et al. 2014; Achigan-Dako et al. 2014; Vira et al. 2015). More than 10 millennia after the emergence of settled agriculture, millions of rural smallholders in most geographical regions of the world are still reliant on wild products from foraging forests and wild lands for their subsistence and livelihoods (Wunder et al. 2014), although a recent study of wild product harvesting by 32 indigneous communities in the Ecuadorian Amazon showed this was declining (Gray et al. 2015). Ickowitz et al. (2014) found a significant positive relationship between tree cover and dietary diversity, suggesting that children in Africa who live in areas with more tree cover have more diverse and nutritious diets. In a comparative analysis of environmental income data collected from some 8000 households in 24 developing countries, Angelsen et al. (2014) highlighted that environmental income accounts for 28% of total household income, with 77% coming from natural forests. Food products (wild fruit and vegetables, fish, bushmeat, mushrooms) were the second most important category (over 30%) and likely to help meet the nutritional, medicinal, utilitarian and ritual needs of many households.

A recent survey summarizing information from 36 studies in 22 countries highlights that wild biodiversity still plays an important role in local contexts with around 90–100 wild species per location and community group. Based on some estimates, the use of wild food reached up to 300–800 species, although actual consumption and dietary intakes were not studied (Bharucha and Pretty 2010). Xu et al. (2004) reported that 283 different species of edible vegetables were found in the markets of Xishuangbanna in southwest China and the trade in wild vegetables contributed between 15% and 84% of market income for different groups. This represented between 4% and 13% of total household income. Notably, the mean price of wild vegetables was 72% higher than that of cultivated vegetables. In South Africa, Shackleton et al. (1998) found that 25% of households sampled in nine villages sold wild vegetables.To investigate the importance of wild foods in Europe, Schulp et al. (2014) analysed the availability, utilization and benefits of wild game, wild plants and mushrooms in the European Union (EU). They recorded a wide variety of game (38 species), vascular plants (81 species) and mushrooms (27 species) collected and consumed throughout the EU.

Wild foods include varied forms of both plant and animal products, ranging from fruits, leafy vegetables, woody foliage, bulbs and tubers, cereals and grains, nuts and kernels, saps and gums (which are eaten or used to make drinks), mushrooms, to invertebrates such as insects and snails, honey, bird eggs, bushmeat from small and large vertebrates, reptiles, birds, fish and shellfish (Bharucha and Pretty 2010; Shackleton et al. 2010). These various wild foods invariably add diversity to the diets of people and communities who make extensive use of them.[1] These examples also reflect broad groups and not the dozens of species included within each wild food type.[2] Abu-Basutu (2013) reported that the species "commonly" used across two villages in southeast South Africa included 17 mammal, 14 bird, 6 fish, 10 leafy vegetables and 7 fruits species. In comparison, Ocho et al. (2012) reported that 120 wild plant species were listed as foods by residents of a single village in southern Ethiopia, with an average of 20 species per household.

[1] In another example, across a sample of 14 rural villages in South Africa, on average, 96% of households consumed wild spinach, 88% ate wild fruits, 54% ate edible insects, 52% consumed bushmeat and 51% ate honey (Shackleton and Shackleton 2004).

[2] For example, more than 100 different plant species are consumed as wild vegetables in South Africa overall (Dweba and Mearns 2011). In northeast South Africa, 45 leafy vegetables and 54 fruits were recorded in a household survey across nine villages (Shackleton et al. 1998, 2000).

However, caution is needed when analysing the extent to which wild biodiversity is available and that actually consumed and contributing to dietary diversity. In some instances, wild foods can constitute a large portion of the diet while in others, actual consumption is limited (Powell et al. 2015). In Benin, for example, the contribution of wild edible plants to total dietary intake was relatively low (Boedecker et al. 2014). More research is needed to determine the conditions and factors that actually determine the utilization and consumption of wild foods and the reasons for which consumption among communities in some biodiverse regions may be low. The use of wild foods is especially relevant where agricultural production is primarily centred on one or two cereals or tuber-based staples that contribute the bulk of daily calorie requirements, but provide limited micronutrient and dietary diversity.

Wild foods are an essential and preferred dietary component in both rural and urban households in many parts of the world.[3] Aberoumand (2009) reports that approximately one billion people around the world consume wild foods, but it is likely to be much higher. It is not only rural communities that make use of and may have preference for wild foods. There are many wild foods in large urban markets. Examples include wild vegetables in West Africa (Mertz et al. 2001; Weinberg and Pichop 2009), Croatia (Luczaj et al. 2013), Turkey (Dogan 2012), Brazil (Kobori and Rodriguez-Amaya 2008), Lebanon (Batal and Hunter 2007), Morocco (Powell et al. 2014), Italy (Turner et al. 2011), and China (Xu et al. 2004), bushmeat in central Africa (Edderai and Dame 2006; van Vliet et al. 2012), fish in the Democratic Republic of Congo (de Merode et al. 2004), and mopane worms in southern Africa (Greyling and Potgieter 2004). These findings show that the consumption of wild foods is not driven solely by need or poverty, but also by culture, tradition and preference.

While the above data and examples show a wide diversity of wild species and food types in diets, the actual proportion of daily nutrient requirements supplied by wild foods relative to grown or bought foods remains largely unknown. It is likely to be significant, however, as many wild food species are much richer in vitamins, micronutrients or proteins than many conventional domesticated species that dominate agricultural or home-garden production (Yang and Keding 2009; Bharucha and Pretty 2010). Kobori and Rodriguez-Amaya (2008) showed the higher carotenoid levels of wild native Brazilian leafy green vegatables compared to commercially produced leafy vegetables. Protein levels in edible insects such as mopane worms (*Imbresia belina*) are approximately double those in beef (Greyling and Potgieter 2004). The same applies to mushrooms, such as *Psathyrella atroumbonata*, which has 77% more protein than beef (Barany et al. 2004). Vitamin C levels in baobab fruits (*Adansonia digitata)* (see Box 4) are also six times higher than oranges (Fentahun and Hager 2009); *Amaranthus*, a widely used green leafy vegetable, has 200 times more vitamin A and ten times more iron than the same-sized portion of cabbage (McGarry and Shackleton 2009b).

Importantly, higher values of vitamins and minerals boost immunity against diseases (Himmelgreen et al. 2009). Golden et al. (2011) reported that bushmeat hunting by households in northeastern Madagascar had a significant impact (by approximately 30%) in lowering the incidence of childhood anaemia and this was more pronounced in poorer households than wealthier households. Most development agencies dealing with food security accept that there is a strong relationship between dietary diversity generally and health and nutrition status, founded on a number of studies globally (e.g. Ruel 2003; Arimond and Ruel 2004; Steyn et al. 2006). Thus, the inclusion of even small amounts of wild foods add to the diversity of the standard diet in many countries, with beneficial effects on health outcomes.

Dealing with the declining intake of grown food types by increasing the quantity and diversity of wild foods in the diet is a common strategy in

[3] For example, the diets of the Turumbu people in the Democratic Republic of Congo are mainly composed of cassava, which they grow, but are supplemented on a daily basis with wild foods such as wild leafy vegetables, bush meat, wild fish, wild mushrooms, caterpillars, ants and honey, depending on the season (Termote et al. 2010).

some parts of the world. For example, da Costa et al. (2013) describe how wild foods increase in prominence in the diet as stores of staple carbohydrate crops decline (maize, rice and cassava) in Timor-Leste. This was regarded as one of the primary food coping strategies for approximately two months of the year. More detailed results are reported by de Merode et al. (2004) for seasonal uses of crops and wild foods in northeastern Democratic Republic of the Congo. They found that during the four-month hungry season the consumption of own agricultural produce declined by 46%, while the use of wild foods increased markedly, 475% for fish, 200% for wild plants and 75% for bushmeat. The value of wild foods traded in the market also increased during the lean season, a 365% increase in fish, 233% increase for wild plants and 155% increase for bushmeat trade. The storing of wild foods has been observed for both plant-and animal-based foods.[4]

Wild species often contain essential nutrients, but information on the composition and consumption of these foods is limited and fragmented (Burlingame et al. 2009) or of poor quality (McBurney et al. 2004). It is therefore difficult to evaluate the contribution of underutilized wild foods to dietary adequacy. Knowledge on the compositional data of these foods is essential in order to promote, market and expand the use of underutilized wild foods, for example, in nutrition-related projects, programmes and policies in the agricultural and environmental sectors. While forest foods cannot be a panacea for global issues related to food security and nutrition, in some specific geographic contexts, they can play a significant role as shown in Box 4.

Box 4: Indigenous fruit trees: the African baobab

Forests and their non-timber forest products (NTFPs), either through direct or indirect provisioning for human nutrition, can contribute to food security, particularly in developing countries. The potential of indigenous food, is mostly derived from wild and underutilized cultivated species, has largely remained untapped due to scant information on the nutritive and economic value of these foods. For example, combining different indigenous fruit tree species in agroforestry systems based on the seasonal calendar of fruit availability could result in a year-round supply of key nutrients (Vinceti et al. 2013; Jamnadass et al. 2013; Kehlenbeck et al. 2013a, b; Jamnadass et al. 2011). A study by Kehlenbeck et al. (2013a) in sub-Saharan Africa shows that consuming 40–100 g of berries from *Grewia tenax* (Forrsk.) Fiori could supply almost 100% of the daily iron requirements for a child under 8 years of age. In addition to micronutrients, the high sugar content of fruits such as tamarind (*Tamarindus indica L*) and baobab (*Adansonia digitata L*) make them important sources of energy. The fruits of *Dacryodes edulis* (G. Don) H.J. Lam, and the seeds of *Irvingia gabonensis* (Aubrey-Lecomte ex O'Rorke) Baill., *Sclerocarya caffra* Sond. and *Ricinodendron rautanenii* Schinz have a higher fat content than peanuts (Vinceti et al. 2013; Johnson et al. 2013).

The occurrence and distribution of the African baobab (*Adansonia digitata*) in drier habitats of Africa, commonly found in savanna, scrubland and semi-desert, has great potential to support communities in more vulnerable dryland ecosystems and in the face of climate variability. The baobab is a majestic tree in the landscape but it is not only its physical presence that exhibits diversity within

[4] For example, Shackleton et al. (1998) reported that the majority of households in rural northeast South Africa dried one or more wild vegetable species and between 20% and 50% dried wild fruits for use in the off season. The role of traditional knowledge associated with wild foods is also important in helping communities cope with lean periods as well as supporting the conservation of wild foods (Sujarwo et al. 2014; Pardo-de-Santayana and Macia 2015).

and between its trees but also the high nutritional value of its fruits. The most important food from baobab is the fruit pulp, which is rich in vitamins and minerals. It can provide far higher amounts of vitamin C, calcium and iron than more common tropical fruits such as mango and orange (Kehlenbeck et al. 2013a). However, there is a large variability in the levels of vitamin C in fruits of different individual baobab trees – from 126 to 509 mg per 100 g edible portion (Stadlmayr et al. 2013) – but even the lowest figure identified is far higher than in many other fruits. In addition to the fruit pulp, baobab also produces leaves that are used as nutritious vegetables and edible seeds, from which oil for consumption and cosmetic purposes are produced (Caluwe et al. 2010).

The potential of baobab for nutrition and income generation is a good example of a new product with high potential in European market, given the acceptance of baobab as a novel food in 2008. Due to its high nutrition potential and demand in consumer markets, research is ongoing in East Africa by the World Agroforestry Centre (ICRAF) to identify populations of baobab, distribution across landscapes, variation in genetic and morphological characteristics, and the diversity of nutritional content within and between wild populations. Information on nutrient content may facilitate the selection of priority fruit tree species for domestication programmes aiming at improving food and nutrition security and for income generation.

While baobab is one example, there are hundreds of other wild food trees in Africa with similar importance for food and nutrition security. Developing and disseminating nutrient-sensitive processing techniques for indigenous fruits can further contribute to rural livelihoods through diversification of income-generating activities and by extending the shelf-life and availability of tree-based food products for consumption during off-seasons. Markets need to be developed for these new products, and processors linked to domestic and international markets to further improve value chain opportunities. However, the abundance of indigenous fruit trees is said to be decreasing in many parts of sub-Saharan Africa due to changes in ecosystem equilibrium and loss of biodiversity as a result of changes in land use, increasing urbanization and climatic shocks, among others. All of these result in shifts in species distribution, altered pest and disease occurrences, and possibly a lack of pollinators (see Box 3) for sufficient fruit tree diversity and occurrence. Domestication and increased cultivation of the most important indigenous fruit tree species may help to both conserve biodiversity and provide rural communities with better livelihood options.

3.2 Sustainable harvest and consumption of wild foods

Wildlife resources such as bushmeat or wild meat (here encompassing non-domesticated terrestrial mammals, birds, reptiles and amphibians harvested in the wild for food) constitute the main source of animal protein in many tropical forested landscapes (Kothari et al. 2015), though the availability of bushmeat resources around urban centres may decline substantially, corresponding with a prevalence in child stunting (Fa et al. 2015). Bushmeat also supplies many important micronutrients in much higher amounts or with higher bioavailability than plant source foods (Vinceti et al. 2013). A study from Madagascar estimated that the loss of bushmeat from the diet of children, without substitution by other sources, would result in a 29% increase in children suffering from iron deficiency anaemia (Golden et al. 2011). It must nonetheless be noted that various activities associated with the handling of bushmeat, its consumption and (illegal) trade also involve varying levels of health risks for disease emergence (Wolfe et al. 2005). In particular , these include activities associated with unsafe hunting, butchering and transport of some species, especially primates (see also chapter on infectious diseases). Moreover, the over exploitation of certain wild animal populations is leading to the depletion of some species (Nasi et al. 2011) and constitutes a rising concern for conservation (Kothari et al. 2015). The resulting mass declines in wildlife, documented by Nasi et al. (2008), is threatening the food security and livelihoods of some forest communities (Heywood 2013), especially where home subsistence consumption is more common than the trade in bushmeat. Interestingly, a study in Liberia, West Africa has found that regions with access to affordable fish protein had higher chimpanzee population densities (Junker et al. 2015) and highlights the importance of integrated approaches to better inform conservation actions. Wild foods such as edible insects also contribute nutritional value to the diet of people in certain regions (van Huis et al. 2013).

Over exploitation or over harvesting is also an area of concern for wild edible and medicinal plant species (see chapter on traditional medicine within this volume), and measures to avert this have been integrated into tools such as FairWild Standard, most often used for medicinal plants, the development of species management plans, plant conservation areas, genetic reserves, community agreements, common property agreements, and so forth (Kothari et al. 2015; Dulloo et al. 2014; Hunter and Heywood 2011; Heywood and Dulloo 2005).

3.3 Wild foods as a coping strategy

Use of wild edible plants and animals (wild foods) is a key coping strategy for many rural households, including in response to shocks, such as crop failure, drought (or other natural disasters), loss of cash income, illness or death of the breadwinner. This coping strategy can be mobilized by one or more of three strategies (Shackleton and Shackleton 2004). The first is for households to increase the direct consumption of wild foods that are already part of their regular diet. For example, a household that normally consumes wild leafy vegetables 2–3 times per week may increase their consumption to 5–6 times per week when faced with a shock that renders them unable to procure the usual purchased or grown foods. The second mechanism is to take up consumption of a wild food that was not normally, or rarely, part of the diet. For example, a household may normally rarely eat bushmeat or wild caught fish, but in the aftermath of a shock may use it as their primary, or only, source of meat until they have recovered. Thirdly, households may collect wild foods and sell them on local or nearby urban markets. The cash earned is then used to help in relieving the impact of the shock.

While many national or regional food security indices or models focus on the net yields of key crops and average those across population demand or calorie needs, these overlook the potentially high variability in the timing of food availability from crops. The colloquially labelled "hungry season" or the "lean season", when food stores from the previous cropping season begin to dwindle, and the new season's crops have not matured is typified by declining calorific intake and a low diversity of grown foods in the diet. During the same period, food prices are high because stocks from the previous cropping cycle have diminished. This combination can result in clear patterns of seasonal nutritional status or malnutrition, exemplified by Devereux and Longhurst (2010) for malnutrition in northern Ghana. This period may also be a time of peak labour demand for the preparation, planting, weeding and tending of the new crops. Tetens et al. (2003) recorded a 17% drop in mean energy intake by adults between the peak season and the lean season in rural Bangladesh. Such seasonal patterns may also be evident in urban populations because of food price increases during the lean season (Becquey et al. 2012). Seasonal nutritional or energy shortfalls can also exacerbate existing health issues such as HIV/AIDS (Akrofi et al. 2012).

There is ample evidence of wild foods being used as coping mechanisms in the face of a household shock. Challe and Price (2009) showed how there was a major shift in primary livelihood strategies of HIV/AIDS-afflicted households in southern Tanzania, from a largely agrarian livelihood (90% of non-affected households; 3% of afflicted households) to a gathering one (0% of non-affected households; 68% of affected ones). This is typically interpreted as a result of the loss of labour for agriculture to grow food (Drimie 2003; Yamano and Jayne 2004). The number of weekly trips to collect wild edible orchids (to supplement their diets or as cash income) also doubled in HIV/AIDS-affected households relative to unaffected ones. McGarry and Shackleton (2009a, b) recorded the use of wild animal foods by children in households with high HIV/AIDS proxy measures relative to households with low, or no, proxy measures. Hunting of wild animals, birds and insects was significantly higher in affected households. In a two-week monitoring period, the consumption of wild mammals was three times higher, wild birds two times higher, reptiles almost double and insects four times higher. Species consumed over the two-week period include two red data species. Over 40% of households also sold some of the wild catch to supplement income.

Hunter et al. (2007) provided qualitative evidence on how surviving members of a household, following an HIV/AIDS death of an adult, turned to procuring a larger proportion of their diets from wild foods. Surviving members stressed the difficulties of food shortages, including reports that "*locusts are now our beef*". The findings also confirmed that food shortages increased as a consequence of severe household shocks, and that household food security generally decreased after the mortality of an adult, with increased reliance on wild foods. Wild foods may also be a coping response to other types of household shocks. For example, the ethnobotanical literature is replete with references to famine foods, namely, those wild foods that were traditionally used in times of drought and crop failure. While dependence on these may have declined to some extent with modern national-scale responses, this reliance persists in some cases. For example, Ocho et al. (2012) list 120 different wild plant species used by people in Konso in southern Ethiopia, of which 25 were generally used in times of food shortages. Similarly, the Yanomani Indians in Venezuela regularly use 20 wild plant species in their diets but consume an additional 20 species during food shortages (Fentahun and Hager 2009). In Botswana, when there is crop failure due to drought, wild fruits also contribute to food security until conditions improve (Mojeremane and Tshwenyane 2004).

5. Biodiversity and traditional food systems

Indigenous peoples' food systems and cultures are good examples of the complexity and remarkable diversity of food availability and utilization. They additionally represent important repositories of knowledge from long-evolved cultures and patterns of living with local ecosystems (Kuhnlein et al. 2009). For centuries, communities of Indigenous peoples have been the custodians of the vast majority of the planet's food and genetic resources, and stewards of the diverse ecosystems and cultures that have shaped these resources. Indigenous peoples' food systems and cultures have often provided for healthy and resilient diets, which have had minimal impact on the environment prior to colonization and development, and for many generations have ensured food security and nutrition. These food systems have not developed in a vacuum and are strongly influenced by the forces of globalization and development (Kuhnlein et al. 2013). The traditional foods they provide are also under threat from the impacts of climate change (Lynn et al. 2013).

Indigenous peoples are often the most disenfranchised, marginalized and poorest members of wider society, and they are targeted by most governments for health improvement and development. Such development often leads to dietary change, including increased reliance on "market foods", which are more often than not highly processed and contribute to increased risk of chronic disease, including obesity and diabetes. This reduced reliance on traditional foods has also led to an erosion of traditional food resources and associated indigenous knowledge. With obvious outcomes for food security, this has significantly affected the welfare, vulnerability and marginalization of indigenous communities. This could be moderated with increased attention to the principles of diet and health already contained within the culture, and with the recognition of the nutrient properties of traditional food resources, and how these foods can be used to best advantage for health promotion (Egeland and Harrison 2013).

Indigenous and local communities have created an enduring relationship with the landscape and its complement of flora and fauna (Turner et al. 2013).[5] Regardless of geographical location, indigenous peoples suffer higher rates of health disparities and lower life expectancy compared with non-indigenous peoples (Egeland and Harrison 2013). Poor diet is a significant contributor to premature death among Indigenous Australians and is considered a significant risk factor for cardiovascular disease, type 2 diabetes, renal disease and cancer. A study into the burden of disease in Indigenous Australians (Vos et al. 2007) attributed 11.4% of the total burden of disease in the indigenous population to high body mass and 3.5% to low fruit and vegetable consumption. In 2012–13, 66% of indigenous Australians over the age of 15 years were overweight or obese, 42% were eating the recommended daily intake of fruit (2 serves) and 5% were eating the recommended daily intake of vegetables (5–6 serves) (Australian Bureau of Statistics 2014). In New Zealand, statistics consistently show Māori as being over-represented in key health areas such as cardiovascular disease, cancer and diabetes, with much of this attributed to lifestyle and dietary choices. New Zealand's latest nutrition survey (2011) highlights that the country's obesity epidemic has increased dramatically over the past decade or so. This survey found that among Māori, over 40% of men were obese while 48% of Māori women were obese. It also found that eight out of the world's top ten countries where obesity is now a problem are in the Pacific region (Ministry of Health 2012).

A study led by the Centre for indigenous peoples' Nutrition and Environment covering 12 indigenous communities in different global regions confirmed the diversity and complexity of indigenous peoples' food systems and diets (Kuhnlein et al. 2009).[6] Strengthening and leveraging these food systems is a strategy that should be considered to improve diets and reverse negative food-related health outcomes. This includes interventions that aim to identify nutritionally rich traditional foods and to promote, mobilize and deliver these foods to target populations. Not only do these food-based approaches potentially improve nutrition and health in a sustainable manner, they also help revive traditional knowledge, biocultural heritage and contribute to the conservation of biodiversity.

A corollary to this is the almost ubiquitous decline in intergenerational transmission of local cultural values, beliefs, institutions, knowledge, practices and language regarding local biodiversity, and the foods and food systems it underpins.

Despite significant animal and plant biodiversity, it cannot always be assumed that a biodiversity-rich environment or landscape necessarily contributes to better diet or enhanced nutrition of individuals living in close proximity (Termote et al. 2012b). Linking biodiversity assessments with quantitative dietary assessments in biodiverse environments should promote more ethnobiological studies to better understand why some local communities do

5 For example, New Zealand, the southernmost landmass of the Pacific region, has a temperate but unpredictable climate with extremes from sub-tropical in the north to sub-Antarctic in the south. Māori, the indigenous people of Aotearoa-New Zealand, on settling in New Zealand from the more tropical Pacific islands to the north, had to adapt their horticultural practices to this new environment and its many limitations. Much of their lifestyle was based on a subsistence approach, including both cultivated and uncultivated plants, and the seasonal harvesting of birds and fish. In light of the growing prevalence of obesity and NCD among the Māori, how to recapture and retain traditional knowledge on traditional food systems is now a high priority for many Māori communities (Roskruge 2014; McCarthy et al. 2014).

6 For example, in Pohnpei, there was major diversity and availability of local species and foods, with 381 food items being documented including karat, an orange-fleshed local banana variety and pandanus varieties rich in carotenoids. The Ingano diet revealed the utilization of over 160 types of food, ranging from roots to insects to palm tree products with milpesos palm, yoco liana, bitter cane and cayamba mushroom found to be a priority for maintaining local health. The Dalit food system revealed a diet highly reliant on wild plant foods with a recorded total of 329 plant species or varieties providing food (Kuhnlein 2009).

not make more effective use of edible biodiversity (Penafiel et al. 2011). Possible barriers include negative perceptions of indigenous wild foods; excessive women's workloads and distances involved for collection; food preparation times; and poor knowledge among local populations about the nutritional value of the indigenous wild foods in their immediate environment. If we are to promote more effective biodiversity interventions it is important to address these barriers by generating and maximizing use of quality data on nutrient composition; increasing awareness of and nutritional education on the benefits of edible biodiversity; domesticating priority species and facilitating their integration into home gardens; and developing guidelines for improved use of nutritionally rich foods from local biodiversity, including recipes adapted to modern lifestyles.

6. Biodiversity and the nutrition transition

Globalization, poverty, modern agricultural practices and changes in dietary patterns have led to a "nutrition transition". The nutrition transition is the process by which development, globalization, poverty and subsequent changes in lifestyle have led to excessive dietary energy intakes, poor-quality diets and low physical activity (e.g. Agyei-Mensah and Aikins 2010). A shift from traditional foods and healthy diets towards consumption of poor-quality processed foods, often available at lower prices, has taken place in many countries (see Box 5). Often this has resulted in the significant loss of biodiversity, and the agroecosystems and knowledge that nurture it, much of it nutritionally superior to the energy-rich and nutrient-poor food products that comprise the more simplified diets resulting from this transformation (Dora et al. 2015). Such dietary shifts are among the complex range of factors that have contributed to the alarming levels of overweight and obesity observed in over 2 billion people globally (Ng et al. 2014), as well as the rise in diet-related chronic diseases such as diabetes and hypertension, which have huge impacts on personal, social and economic development. It has been estimated that the costs of dealing with diet-related NCDs globally between 2011 and 2030 will be around US$ 30 trillion (Bloom et al. 2011). The complex issues contributing to the alarming rise in obesity and equally complex approaches to reversing the obesity pandemic are dealt with in detail in The Lancet Obesity 2015 Series (see, for example, Swinburn et al. 2015; Lobstein et al. 2015 in that issue).

The nutrition transition is particularly prevalent among indigenous peoples, who tend to suffer higher rates of health disparities and lower life expectancy, regardless of geographical location (Egeland 2013) and across many other populations in low-and middle-income countries. A recent study out of Australia (Australian Bureau of Statistics 2014) found that compared with the non-indigenous population (and after adjusting for age differences), aboriginal and Torres Strait Islander people were:

- more than three times as likely to have diabetes (rate ratio of 3.3);
- twice as likely to have signs of chronic kidney disease (rate ratio of 2.1);
- nearly twice as likely to have high triglycerides (rate ratio 1.9), more likely to have more than one chronic condition, for example, both diabetes and kidney disease at the same time (53.1% compared with 32.5%).

In many parts of the world, this nutrition transition is accompanied by increased consumption of meat, total fat and trans-fatty acids, sugar and sodium, components that have contributed to the dramatic emergence of obesity and associated chronic diseases (Ho et al. 2008; Eilat-Adar et al. 2008; Haddad et al. 2014). Others also highlight that the links and interactions between diet and obesity may be more complex than this, with diets excessively high in sugars and carbohydrates altering the gut microflora to selectively favour bacterial groups such as *Firmicutes*, which are better at processing these types of foods and converting them to calories with the consequence that the obese gut microflora is much less diverse (DeClerck 2013; Clark et al. 2012; Delzenne and Cani, 2011). As the chapter on microbial diversity within this volume

Box 5: Diet simplification in the Philippines

Results from the Philippine National Nutrition survey suggests that the nation's diet is consistent with the world phenomenon of diet simplification, that is, less complex and high-energy diets (Frison et al. 2010). Food consumption data from 1978 to 2003 show the dietary pattern of Filipinos comprised rice, fish and vegetables. Changes in proportions of these food items, however, led to energy-dense density diets. Alongside this, there is a downward trend in the consumption of fruits and vegetables. Intake of starchy roots and tubers was halved from 1978 to 2003 (Pedro et al. 2006). On the other hand, there is increased consumption of meat, fats and oil, milk and sugars. This pattern, described as the nutrition transition, is also seen in other developing countries (Popkin 2001; Popkin et al. 2012). Recent diet diversity studies among Filipino children also reflect simplified diets as diet diversity score results are found to be below cut-off points (Kennedy et al. 2007; Talavera et al. 2011). It should be noted that low scores indicate unsatisfactory nutrient adequacy (Hoddinott and Yohannes 2002; Ruel et al. 2004; Steyn et al. 2006). This lack of diet diversity is multi factorial (i.e. lack of purchasing power, unavailability in the markets, unfamiliarity with certain food items, lack of know-how on to prepare/consume them). The nutrition transition, together with intensive agriculture and environmental pressures, is also attributed to reduction in dietary diversity and the accompanying loss in agricultural biodiversity and associated traditional knowledge (Gold and McBurney 2012).

also indicates, further exposure to the microbial diversity in the environment may also contribute to the development of *Firmicutes*, particularly lactobacilli and the regulation of immune responses (Lewis et al. 2012). More recently, scientists have shown that the gut microbiome is much more diverse in rural Papua New Guineans compared to people living in the United States and attributed this to a western lifestyle, hygiene and diet (Martinez et al. 2015). Similar observations regarding gut microbiota diversity have been made among pre-contact Yanomami Amerindians in the Amazon (Clemente et al. 2015). As also noted in the chapter on agricultural biodiversity within this volume, shifts to livestock intensification and diets dominated by meat consumption also impact negatively on ecosystems and biodiversity, and are associated with an increased risk of NCDs, including cardiovascular disease and some types of cancer (World Cancer Research Fund 2007).

Some of the highest rates of obesity and growing burden of NCDs can be observed in the Pacific region (Snowdon and Thow 2014) where many small island states have undergone major changes in traditional diets, to the extent that they are largely reliant on less healthy food imports (see Box 6). In this region, it is estimated that NCDs account for 75% of deaths, while there are signs that life expectancy in some countries is slowing, even declining, as a consequence of NCDs (Snowdon and Thow 2014).

Key recommendations from The Lancet Obesity 2015 Series include efforts to ensure healthy food environments and food systems through approaches that protect healthy food preferences from market intrusion – such as policies that promote healthy food services in schools and early childhood settings – and approaches that allow people to satisfy their healthy food preferences through food policies that place taxes on unhealthy foods or support good access to fresh nutritious foods (Swinburn et al. 2015; Lobstein et al. 2015). In Mexico – where the proportion of overweight women between the ages of 20 and 49 years increased from 25% to 35.5%, and where almost 30% of children between the ages of 5 and 11 years are considered overweight – the government, under pressure to address the growing health crisis, passed a bill to apply taxes on high-calorie packaged foods (including peanut butter, sweetened breakfast cereals and soft drinks). More sustainable and complementary actions

Box 6: Dietary change and the rise of NCDs in the Pacific

The Federated States of Micronesia (FSM) have witnessed significant dietary shifts from nutritious and diverse local staples to an increased dependence on imported, often unhealthy, foods in the past few decades, with up to 40% of all imports being food imports in 1986 (Englberger et al. 2003d; 2011). In 2007, it was the second most obese country in the world, with pockets of vitamin A deficiency being among the highest worldwide, despite its abundance of local nutritionally rich local foods, including 133 varieties of breadfruit, 55 of banana, 171 of yam, 24 of giant swamp taro, nine varieties of tapioca and many varieties of pandanus in the state of Pohnpei alone (Englberger and Johnson 2013). There was little evidence of malnutrition, diabetes or hypertension before the 1940s, with vitamin A deficiency not documented until 1998, indicating the likelihood that these were not problems . Englberger et al. (2003d) argue that it was not until a number of US initiatives started in the 1960s that issues of dependency on imported foods and dietary shifts began and, by 1985, the national school feeding programme provided meals to 30% of its population based largely on food imports. While access to more diversified foods is not without its benefits, an over reliance on imported foods threatens food security, sometimes leading to foods with lower nutritional quality, and can contribute to the chronic NCD burden (borne by an already overburdened national economy), and undermine traditional coping mechanisms and contingency planning developed by communities to deal with periods of food insecurity. Unfavourable food and trade policies often exacerbate these problems. Imported chicken and turkey tails are commonly eaten in FSM. These are fatty off-cuts, which are not marketed or consumed in their countries of origin because they are considered "health damaging products" and the practice of selling in the Pacific is seen as a form of "food inequality" considered by some as inappropriate "food dumping" (Hughes and Lawrence, 2005; Jackson, 1997). Such practices in the Pacific have prompted a range of trade-related food policy initiatives aimed at creating a healthier food environment (Thow et al. 2010; Snowdon and Thow 2014).

to encourage healthy local food alternatives are needed (GRAIN 2015), despite the government's efforts to put in place food regulations that aim to improve the availability and accessibility of healthy foods in schools (Roberto et al. 2015). One example of an initiative to create healthy food environments in schools has been the Brazilian government's changed food procurement policies during President Luiz Inacio Lula da Silva's term, which favour and support the production and consumption of non-processed, fresh and locally produced foods and provide greater equity to farming families (Roberto et al. 2015). Swinburn et al. (2015) also point out that the early momentum to better link agriculture and nutrition[7] must be maintained in order to achieve the goal of healthy, sustainable, equitable and economically viable food systems. Among other things, this should include efforts to concentrate on the preservation and strengthening of national food sovereignty and agro-food biodiversity, and the creation of sustainable diets. They also emphasize the need to include global goals to reduce obesity and NCDs in the UN's Post-2015 Development Agenda.

[7] See Key recommendations for improving nutrition through agriculture and food systems. http://www.fao.org/fileadmin/user_upload/nutrition/docs/10Key_recommendations.pdf

7. Nutrition, biodiversity and agriculture in the context of urbanization

By 2050, it is estimated that about 6.3 billion people will inhabit the world's towns and cities, marking a rise of 3.5 billion from 2010, and the total urban area is expected to triple between 2000 and 2030 (CBD 2012). This will present great challenges for sustainable food production and consumption, and food systems in general. A 2014 study using spatial overlay analysis, integrating global data on croplands and urban areas, estimates the global area of urban and peri-urban irrigated and rainfed croplands to be about 24 Mha (11% of all irrigated croplands) and 44 Mha (4.7% of all rainfed croplands), respectively. This clearly demonstrates an important role for food production and security in urban areas (Thebo et al. 2014). As urbanization continues to rise, both terrestrial and aquatic ecosystems may be increasingly threatened (Boelee 2011). This urbanizing trend has corresponding implications for food and nutrition security, as estimates indicate that urban inhabitants are likely to shift to diets that are more energy, calorie and protein intensive, further exacerbating the risks of obesity, including in low-and middle-income countries (Popkin et al. 2012). Despite these risks, urban spaces also present considerable opportunities to promote greater conservation and use of biodiversity, including mainstreaming of biodiversity into city landscapes and city food systems, as exemplified by recent discussions for an urban food policy pact (UFPP); an emerging global initiative to "feed cities" in a more just, healthy and sustainable way.[8] Peri-urban locations may already be important areas where crop diversity survives (Elyse Messer 2015).

It is estimated that around 15% of the world's food is currently grown in urban and peri-urban areas, including backyards, roof-tops, balconies, community gardening in vacant lots and parks, urban fringe agriculture and livestock grazing in open spaces (Gerster-Bentaya 2013). A case study to determine the potential of rooftop garden vegetable production in the city of Bologna found that it could satisfy 77% of its residents' needs and that besides this contribution to food security and nutrition of the city, the potential benefits of rooftop gardens to urban biodiversity and ecosystem service provision could also be substantial by facilitating green corridors connecting biodiversity-rich areas across and close to the city (Orsini et al. 2014).

There is a direct relationship between biodiversity and food security in cities. Biodiversity and small-scale production in urban food systems play a critical role in the fight against hunger and diet-related health problems, and is pivotal in developing resilient city-regional food systems. Yet the rapid growth of cities is challenging the provisioning capabilities of agriculture and modifying food systems at local and global levels, while at the same time, a shift in urban diets to less diverse and more processed foods has increased the incidence of NCDs such as obesity and diabetes. The expansion of urban populations will dramatically increase global demand for food of a non-subsistence nature while continuing urbanization will put pressure on existing food production, potentially increasing land-cover change and threatening biodiversity unless carefully managed. Increasing biodiversity in our existing food systems is critical to maintaining healthy global food systems and the ecosystem services they depend on, and to improving global food security (CBD 2012).

With increasing urbanization and rural-to-urban migration, the provision of a healthy and balanced diet will require an increase in urban agriculture. In the Kibera slums of Nairobi, Kenya, households have recently begun a new form of urban agriculture called "sack gardening" in which neglected and underutilized but highly nutritious indigenous vegetables can be planted into large sacks filled with topsoil, which can

[8] At the time of writing, discussions were under way on the implementation of the UFPP, which will be implemented by Milan's city government over the next five years. It was being drafted through a broad participatory process, beginning with an assessment of the strengths and weaknesses of the city's food system. See for example: http://www.ipsnews.net/2015/04/expo-2015-host-city-promotes-urban-food-policy-pact/

contribute to household food security, increase dietary diversity and reduce the need to resort to other coping mechanisms used during food shortages (Gallaher et al. 2013). One of the remarkable success stories of linking agricultural biodiversity to urban markets have been African leafy vegetables (ALVs). A project to promote ALVs in urban markets in Kenya in 2003 resulted in significant impacts and outcomes. Growers around Nairobi who were trained to produce high-quality ALVs for city supermarkets saw their incomes increase twenty fold while sales of ALVs in Nairobi increased by a staggering 1100% (Cherfas 2006). The IndigenoVeg network, targeting urban and peri-urban areas, was also successful in promoting African indigenous vegetables (Shackleton et al. 2009).

The urban street food sector can also play an important role in urban food security and nutrition. For example, the urban vendors in Madurai who sell ready-to-eat, healthy millet-based porridges have improved access to nutritious foods and created livelihood opportunities for the urban poor (Patel et al. 2014). Roberto et al. (2015) also highlight that local governments are increasingly using urban planning processes to ensure that new residential and commercial developments have adequate access to healthy food markets such as farmers' markets and mobile vendors of healthy foods.

In developed countries such as Australia and the UK, approaches to urban agriculture have focused on biodiversity, localization, farmer's markets, community gardens and the viability of farms that occupy or surround cities. In 2008, the City of Melbourne endorsed the *Future Melbourne Plan* which links production, biodiversity and sustainable consumption by setting out an ambitious target of 30% of food to be either grown within the city or sourced from within 50 km of the city by 2020. There are now over fifty accredited farmers, markets in the larger Victoria area supplied by some 2000 farmers. Twelve of these farmers markets are located within Melbourne's suburbs, eight within 125 km of the city, and the rest in rural and regional areas. Rare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breeds sold at farmer's markets around Melbourne include critical, endangered or vulnerable pig breeds such as the Wessex Saddleback, Large Black and Tamworth as well as "at risk cattle breeds such as the Belted Galloway. Melbourne farmers" markets contain far greater diversity of plant varieties and animal breeds than can be found in mainstream supply chains. A network of community gardens further adds to initiatives that make available additional nutritious fruit and vegetable biodiversity to low-income households (Donati et al. 2013).

In the UK, the Incredible Edible Todmorden initiative encourages the novel concept of open-source food, through "permission gardens" and "guerilla gardens", which consist of picking and eating foods others have planted and nurtured. Under this initative, forty public fruit and vegetable gardens that promote awareness about the benefits of food biodiversity, dietary diversity and nutrition were created. It also held a variety of communication and awareness-raising events, including street cook-offs, "Tod Talks", targeted campaigns such as "Every Egg Matters", which maps local egg production, cooking courses, the field-to-plate lunch, and seed swaps. Regular newsletters, an active website, presentations beyond the local district, and veggie tourism also serve to maintain the momentum of the initiative (Paull 2013).

8. Food cultures: local strategies with global policy implications

There is ample evidence of how monocrop, low-diversity agriculture, the shift toward urbanization and the depletion of natural resources, including our marine resources, has led not only to the erosion of our terrestrial, freshwater and marine ecosystems but also of traditional food cultures in many parts of the world (Anderson 2010; Petrini 2013). This has dramatically changed our relationship with food and challenged many of the cultural norms, customs and traditions which have governed how we grow and consume food. This has led to significant changes in our food choices, the amount of different foods we eat, the order in which we eat, when and with whom (Pollan 2008). In some parts of the world this has led to a growing Slow Food movement as described in Box 7.

Box 7. Slow Food and Torre Guaceto, Italy Marine Protected Area: a model to promote food cultures, health and sustainable use

Slow Food, a grassroots organization now spanning over 150 countries, is aimed at preventing the disappearance of local food cultures and traditions, counteracting the rise of "the fast life", homogenizing food production, intensive industrial agricultural crops based on monoculture, and promoting interest in food's origins and cultural traditions at all levels of production and consumption (Petrini 2013; Schneider 2008; Kinley 2012). The selection of Slow Food products is based on an established set of criteria and a continuous exchange of information with local stakeholders to ensure social–cultural, environmental and economic sustainability.

Several approaches have been used to evaluate the sustainability and nutritional impact of these products. Recently, Pezzana et al. (2014) combined nutritional and multi-criteria sustainability to define the Life Cycle Assessment of Slow Food Presidia products. The study found "high levels of sustainability" and additional nutritional value of Slow Food products, and the value of multifactorial approaches in the analysis of the food–health–sustainability relationship (Pezzana et al. 2014).

Presidia products focus on key issues of interest for small-scale agriculture and farming, including the protection of mountain pastures and pastoral farming, defence of traditional landscapes and propagation of traditional seeds by communities, protection of small-scale onshore fishing, transparent labelling, ecologically sustainable packaging and the preservation of traditional artisanal knowledge linked to processing methods.

Examples include small-scale artisanal fishing, which uses low-impact fishing gear and regulates exploitation; it is part of the Mediterranean identity, employing half-a-million people in the region, promoting sustainable fishing practices and allowing fish stocks to recover. Sustainable fishing also implies the need to consider the conservation of marine species, production chains, ecological communities, and the human communities that support and rely on them for food, nutrition and income.

The 22 km2 marine protected area (MPA) of Torre Guaceto is a successful example of the benefits of Slow Food for local communities. Initially established as a no fishing MPA in 1991, its enforcement became effective only in 2000 when the MPA authority and local fishermen struck an agreement to implement a five-year fishing ban, allowing fish to repopulate and habitats to recover (Guidetti 2010). Fishing gear and practices that caused the least damage to marine species and habitats were enforced. By the end of 2005, striped red mullet (*Mullus surmuletus*), large-scaled scorpionfish (*Scorpaena scrofa*) and other taxa also rebounded (Guidetti 2010). Once the reserve partially reopened, local fishermen began to haul in catches more than twice the size of those outside the reserve (PISCO 2011).

Local MPA management authorities can also help fishing communities to increase income opportunities where these are limited by seasonal variations or local preferences. For example, the Torre Guaceto MPA Municipality of Carovigno is far from large markets, some catch, including mullets (family Mugilidae), are not a local favourite year-round, making market value and income highly variable. Collaboration between the MPA Authority, the Slow Food Association and the Fishermen Cooperative of Carovigno in 2014 led to the production of mullet fillets in extra virgin olive oil in glass jars, to stimulate quality and sustainable production of mullet processing for a broader market.

This offers a good example of how local communities benefit from MPAs, which are critical for their protection, and how co-management schemes within protected areas may in turn deliver co-benefits to ecosystems and local communities. These may reduce competition for shared fishing resources, promote foods high in nutritional value, and support livelihoods and the conservation of food cultures. These initiatives are important to jointly increase awareness, sustainability and social acceptance of MPAs, and maximize benefits for local populations.

Pockets of traditional food culture remain strong in many parts of the world despite economic, social and cultural change. Where people still retain a close connection with the landscape. Where biocultural refugia continue to exist, which safeguard the diversity of food-related practices for food and nutrition (Barthel et al. 2013). The East Pokot and Isukha communities in Kenya constitute examples for rich traditional food cultures with manifold associated traditions, beliefs, taboos and practices based on living in a biodiverse environment. More than 130 foods of plant, animal and fungal origin have been reported, which are used and prepared in many different ways (Maundu et al. 2013a; 2013b;2013c; 2013d, see also chapter on traditional medicines). Another example of retained traditional food culture can be found in the harsh geography of the Pamir Mountains of Afghanistan and Tajikistan, where biodiversity plays a very large role in sustaining life and the environment has shaped a system that is uniquely suited to this region and which, in turn, has fostered the development of a rich source of skills and resilience in its people (van Oudenhoven

& Haider 2015). In Indonesia, the Centre for Food and Nutrition Studies of the University of Gadjah Mada (UGM) is documenting food diversity and traditional knowledge among communities in Yogyakarta. Closely linked to cultural and religious festivals, food culture is very much alive in rural communities where ten local root crops are still widely consumed by the young and old. Efforts are being made to establish links between these foods and healthier diets and to promote these local alternatives to imported convenience foods[9].

There are examples where traditional foods and the food cultures which have embraced them have contributed to sustainable and healthy diets as well as healthy lifestyles – in fact, the term diet originates from the Greek *diaita* meaning way of life or lifestyle (UNESCO 2010). The Mediterranean diet has recently been recognized by UNESCO as an intangible heritage of humanity in Spain, Greece, Italy, Cyprus, Croatia, Portugal and Morocco in order to preserve the Mediterranean food culture (UNESCO 2013). The nutritional and cultural model of the Mediterranean diet is characterized by skills, knowledge, practices and traditions that concern obtaining food from the landscape to the table, and that have remained constant over time and space (UNESCO 2013; Petrillo 2012). Besides the nutrition and health benefits of the Mediterranean diet, Tilman and Clark (2014) highlight its environmental benefits by showing, among others, that diet-related greenhouse gas emissions per kilocalorie from "cradle to farm gate" are nearly 25% lower compared to a western omnivorous diet. South Korea is another example of a country that has retained much of its food culture and traditional dietary habits despite change (Lee et al. 2002). It is estimated that more than half of the population still follows the traditional dietary patterns, making the nutrition transition in South Korea unique (Song & Joung 2012; Lee et al. 2002). The traditional diet is characterized by high intake of fruits and vegetables (especially fermented *kimchi* rich in antioxidants, vitamins and minerals) and low intake of total fat (Lee et al. 2002; Lee et al. 2001). In fact, vegetable consumption is among the highest in Asia. There is hardly any Korean dish without vegetables and over 300 types of vegetables are eaten in rural areas, including wild greens like Chinese bellflower and bracken, field-grown greens like shepherd's purse and wild garlic, and cultivated vegetables like squash, eggplant and cucumber (Lee et al. 2002). The inherent biodiversity of this traditional diet has beneficial health effects resulting, for example, in low adult obesity levels (Lee et al. 2002) as well as a 33% and 21% decreased risk of having elevated blood glucose and elevated blood pressure, respectively, compared to a westernized "meat and alcohol"-based diet (Song & Joung 2012). Okinawa, the most southern prefecture of Japan, is widely known for its population that is characterized by long average life expectancy, large number of persons reaching the age of 100 years, and low prevalence of age-associated diseases. These positive characteristics are mainly associated with the traditional Okinawa diet and its deeply embedded biodiversity, which is nutritionally dense and low in calories due to high consumption of phytonutrient-and antioxidant-rich fruits and vegetables (Willcox et al. 2009). The Okinawa food culture comprises many traditional foods, herbs or spices derived from local ecosystems and consumed on a regular basis (such as white-skinned or purple sweet potatoes, local bitter melons or green seaweed) which are classified as "functional foods" ("food is medicine" is intrinsic of Okinawan culture) due to their, among others, anticancer, antidiabetic, antiviral, anti-inflammatory and immune-enhancing properties (Willcox et al. 2009; Sho 2001).

The New Nordic Diet (NND)[10] was recently developed in Nordic countries in collaboration with a world-leading Copenhagen gourmet restaurant to promote a food-based dietary concept that emphasizes gastronomy, health and the environment (Poulsen et al. 2014). Based on traditional food culture and dietary habits, the NND strongly relies on diverse, regional foods in season such as berries, cabbages, pears,

9 See Traditional Root Crops in Indonesia (http://www.b4fn.org/case-studies/traditional-root-crops-in-indonesia/) and many other related case studies of food cultures.

10 http://newnordicfood.org/about-nnf-ii/new-nordic-kitchen-manifesto/

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apples, root vegetables, oats, rye, and fish – all of them traditional Nordic foods that have been found to have beneficial nutrition and health effects (Poulsen et al. 2014; Olsen et al. 2011). Preliminary evidence shows that compliance with NND and its traditional healthy foods is related to decreased mortality among Danes aged 50–64 years (Olsen et al. 2011), increased weight loss and improved blood pressure reduction in centrally obese individuals (Poulsen et al. 2014), and significantly higher micronutrient intake (e.g. iodine 11%, vitamin D 42%) among schoolchildren aged 8–11 years compared to control groups (Andersen et al. 2014). Furthermore, estimates from Denmark indicate that shifting from the average Danish diet to NND leads to overall socioeconomic savings of €42–266/person per year due to reduced environmental impacts and their associated costs (Saxe 2014). The example of NND shows that culturally appropriate dietary patterns based on local and traditional biodiverse foods can successfully be developed in order to reach societal nutritional goals as well as decrease environmental impacts (Saxe 2014; Bere & Brug 2009).

9. Mainstreaming biodiversity for food and nutrition into public policies

Policy support is essential for making changes sustainable. Nutrition and biodiversity offer better opportunities to mainstream biodiversity into policies, programmes and projects. They include the commitments made at ICN2 of countries to improve nutrition, e.g. by fostering the relation between nutrition and agriculture through "nutrition-sensitive agriculture" where biodiversity has an important role to play. Another major achievement in the agriculture sector is the endorsement of the Voluntary Guidelines for Mainstreaming Biodiversity into Policies, Programmes and National and Regional Plans of Action on Nutrition (Guidelines) in 2015 by the Commission on Genetic Resources for Food and Agriculture (CGRFA)[11].

The Food Acquisition Programme (PAA) and the National School Meals Programme (PNAE) in Brazil are two public policy instruments that support family farming by acquiring family farm

[11] http://www.fao.org/3/a-mm464e.pdf

products and directing them to public programmes and social organizations. Both instruments also provide incentives for greater integration of biodiversity and have demonstrated that public policy can be used to address food security while supporting family farming, improving nutrition and encouraging biodiversity conservation.

By 2014, more than US$ 3.3 billion had been spent on the purchase of over 3 million tonnes of food under the PAA, with an average of 80,000 farming families/year involved in the programme. The PAA is currently being implemented in approximately 48% of Brazilian municipalities.

In 2014, 619 of Brazilian municipalities (11%) were assisted, reaching more than 3,900 governmental and non-governmental organizations, including schools, child care organizations, nursing homes and community kitchens.[12] An estimated 15 million people/year benefit from food distribution under the programme. The PAA has contributed to promoting dietary diversification (including fruits and vegetables), sustainable management of biodiversity for food and nutrition on family farms, and the recovery and promotion of neglected and underutilized regional and local biodiversity foods. In schools, the PAA ensures that fresh, locally produced, often organic food, more compatible with local food cultures, is also made available in canteens. The programme has also contributed to the validation and documentation of threatened traditional knowledge, food customs and local cultures associated with these foods, and foods such as babassu palm (*Attalea speciosa*) flour, baru nut (*Dipteryx alata*) flour, cupuaçu (*Theobroma grandiflorum*), palm hearts, umbu (*Spondias tuberosa*), maxixe (*Cucumis anguria*) and jambú (*Syzygium* sp.) are being served more frequently in schools and social care organizations (Grisa and Schmitt 2013). While the nutritional impacts have yet to be fully assessed, preliminary PAA survey results indicate improvements in dietary diversity and health status of target families.

The Ministry of Education through the National Fund for Education Development (FNDE) is responsible for the PNAE, which aims to meet the nutritional needs of schoolchildren, and is considered one of the largest school feeding programmes in the world. By 2012, it is estimated that the programme assisted over 43 million schoolchildren. In 2009, the PNAE decreed that at least 30% of the food purchased through its programme must be bought directly from family farmers, which may encourage the use of native species, and promote local and regional biodiversity. The FNDE also supports efforts through the promotion of school gardens to improve awareness about food production and healthy eating habits.

In Brazil, other relevant instruments to mainstream biodiversity for food and nutrition also include the Food and Nutrition National Policy (PNAN), National Plan for the Promotion of Socio-biodiversity Product Chains (PNPSB) and Development of Organic Agriculture (Pro-Organic). A key component of this effort is to carry out nutritional composition analysis of prioritized native edible species, both wild and cultivated, to demonstrate that these species are rich in nutrients and to use this knowledge base to bring biodiversity conservation and its sustainable use into these different public policies, and provide added incentives for procurement and use in school feeding. Brazil, with the assistance of the Biodiversity for Food and Nutrition (BFN) Initiative[13], will establish the nutritional composition data of over 70 native species prioritized by the Plants for the Future initiative, and those included in the PNPSB. This includes, baru (*Dipteryx alata*), buriti (*Mauritia flexuosa*), cagaita (*Eugenia dysenterica*), mangaba (*Hancornia speciosa*) and pequi (*Caryocar brasiliense*). It also includes Umbu (*Spondias tuberosa*) from the Caatinga biome, and cupuaçu (*Theobroma grandiflorum*) and pupunha (*Bactris gasipaes*) among others. This initiative is also working in partnership with university-based Collaboration Centers on School Food and Nutrition (CECANEs),

[12] http://www.conab.gov.br/OlalaCMS/uploads/arquivos/14_09_15_16_03_05_artigo_evolucao_do_paa_2.pdf, http://www.conab.gov.br/OlalaCMS/uploads/arquivos/15_03_23_15_42_09_sumario_executivo_2014_revisado.pdf

[13] http://www.b4fn.org/

which are linked to the PNAE. To this end, Brazil is building national capacity to facilitate the setting up of "Regional Centres for food composition data" within federal universities to strengthen integration and mainstreaming of biodiversity into relevant policies, programmes, and initiatives focused on food and nutritional security, and on the promotion of a healthy, diversified and sustainable diet. Collaboration is also under way with the FNDE School Garden programme to promote awareness and appreciation of native biodiversity for food and nutrition.

The BFN Project in all participating countries has been active in drawing attention to the importance of biodiversity for food and nutrition in another important national policy instrument aimed at the sustainable use and conservation of biodiversity: National Biodiversity Strategies and Action Plans (NBSAPs).

10. Global policy initiatives

The decades of unsustainable nutrition-related interventions, not to mention outright failures, from both the agriculture and health sectors has prompted new thinking in many relevant areas (McDermott et al. 2015). Nevertheless, mainstream nutrition has largely continued to focus on malnutrition solutions that take little or no heed of long-term sustainability or biodiversity, and have relied principally on supplements, therapeutic formulations, nutrient fortificants for staple or convenience foods, and biofortification through conventional plant breeding or genetic modification (Lancet series 2008, 2013). At the same time, refreshingly new perspectives on these problems and challenges have been emerging from ecologists, among other fields, on the need to better integrate the disciplines of nutrition, agronomy, ecology, economics with nutrition and human health, agriculture and food production, environmental health and economic development to address the multiple goals of reducing malnutrition, promoting sustainable agricultural and food production and environmental protection, often called eco-nutrition (Wahlqvist & Specht 1998; Deckelbaum 2011; Deckelbaum et al. 2006) or nutrition-sensitive agriculture (ICN2). Sustainability was featured as an important issue in many sectors, but in nutrition it was not clear how to proceed. As the health sector's individual nutrient approach and the agriculture sector's food production approach were not leading to improved nutritional outcomes, the focus had to turn to "diets" as the fundamental unit of nutrition.

Biodiversity was the theme of the First International Conference on Sustainable Diets motivated by the growing awareness of the alarming pace of biodiversity loss, ecosystem degradation and their negative impacts on health and development. The Conference provided a forum for consolidating the state of knowledge and advancing the thinking with a multidisciplinary focus. In addition to the scientific sessions, two working groups were convened: one to work on the draft definition of sustainable diets and the other to develop a code of conduct (or code of practice). A consensus definition of sustainable diets, adopted at the First International Conference on Sustainable Diets, acknowledged the interdependencies of food production and consumption with food requirements and nutrient recommendations, and reaffirmed the notion that the health of humans cannot be isolated from the health of ecosystems. Biodiversity was included as an important component of the definition (see Box Definition of sustainable diets).

> *Definition:* **Sustainable Diets** are those diets with low environmental impacts, which contribute to food and nutrition security and to a healthy life for present and future generations. Sustainable diets are protective and respectful of biodiversity and ecosystems; culturally acceptable; accessible; economically fair and affordable; nutritionally adequate, safe and healthy; while optimizing natural and human resources.

At the same time, Working Group 2 prepared a preamble and an outline for what might one day be developed and adopted as a code of conduct or practice. It was modelled on the WHO International Code of Marketing of Breast-milk

Substitutes (WHO 1981). Text from that preamble included the following statements:

- Conscious that food is an unequalled way of providing ideal nutrition for all ages and life stages;

- Recognizing that the conservation and sustainable use of food biodiversity is an important part of human well-being;

- Considering that when ecosystems are not able to support healthy diets, there is a legitimate use of supplements and fortificants; but when ecosystems are able to support healthy diets, nutrition programmes, policies and interventions supporting the use of supplements and fortificants are inappropriate and can create or exacerbate malnutrition, and that the marketing of these food substitutes and related products can contribute to major public health problems.

A platform for action was also conceived at the Conference, with the aim to improving the evidence base for biodiversity and nutrition. This has led to research partnerships involving FAO, the Centre International de Hautes Études Agronomiques Méditerranéennes (CIHEAM), Biodiversity International, INRA (Institut National de la Recherche Agronomique) and others, to develop methods and indicators for the characterization of different agro-ecological zones for sustainable diets (Dernini et al. 2013). These studies are fostering new ideas for building consensus on research and actions needed to link human nutrition with biodiversity, ecosystems and environmental impacts. Some examples include new metrics for nutritional diversity of cropping systems, nutrient diversity within species in major food crops, sustainability of the food chain from field to plate, traditional food system and nutrition security (Ignatius 2012), underutilized fruit for human nutrition and sustainable diets, and conservation systems for plant biodiversity for sustainable diets (FAO, 2012).

The Second International Scientific Symposium on Sustainable Diets featured livestock as its theme (FAO 2013b). The biodiversity of food animal species and breeds was presented, along with the synergies and interdependencies between livestock and the biodiversity of pasture and grazing lands. Features included new data on the nutrient content of milk and meat from the native horse breed of Mongolia, with its high n-3 fatty acid content; and similarly new data on the n-3 fatty acid content of the pasture plants upon which the horse feeds. Together, the genetic trait of the mare and the grassland species provide the essential fatty acids commonly thought to be found almost exclusively in marine species to the population of this landlocked country (FAO 2013b; Minjigdorj et al. 2012).

The Mediterranean diet is being used in some of these studies as a model for sustainable diets, with "biodiversity" featuring in the most recent version of the Mediterranean diet pyramid (Bach-Faig et al. 2011), and as a key component in developing methods and indicators (Dernini et al. 2013). In their analysis using 50 years of global-level data for over 100 countries to quantify the relationship between diet, NCDs and environmental sustainability, Tilman and Clark (2014) found that dietary changes have considerable potential to reduce both the incidence of NCDs and environmental impacts. Their review illustrates a significant reduction in some selected negative health outcomes, including type II diabetes, cancer incidence and mortality due to heart disease, for three alternative diets: a pescetarian diet; a vegetarian diet; and Mediterranean diet when compared to a reference diet including all food groups. Other studies confirm these conclusions (e.g. Katz and Meller 2014; Maillot and colleagues 2011). Such findings have important implications for both the health and conservation sectors. Further integration of these considerations is needed for the development of robust strategies and policies targeting a reduction in the global burden of NCDs.

The sustainability of a diet is heavily determined by interrelated factors categorized as agricultural, health, sociocultural, environmental and socioeconomic; so changes to one affect the others. This complex relationship makes understanding how sustainable diets can contribute to food security and sustainable development agendas difficult (Johnston et al. 2014). Metrics and guidelines that form the basis for wider application are needed to aid decision-making processes at regional and national scales (Prosperi et al. 2014), and to better understand the synergies and trade-offs between dietary diversity, agricultural biodiversity and associated ecosystem functions (Allen et al. 2014; Remans et al. 2014).

A clear consensus has been reached in the nexus between agriculture, health and environment, that the sustainable diets rationale, with biodiversity at its core, along with education and policies, is fundamental to the achievement of the broader goals of sustainable development, connecting nutritional well-being of the individual and of the community to the sustainability of feeding the planet (UN 2012). The UN Secretary General's Zero Hunger Challenge, which links sustainable food systems and hunger reduction, is critical, as the world moves from the largely unmet Millennium Development Goals to the post-2015 Development Agenda. And in his final report to the United Nations, the Special Rapporteur on the Right to Food issued a key recommendation, "To reshape food systems for the promotion of sustainable diets and effectively combat the different faces of malnutrition" (Human Rights Council 2014).

In 2004, the CBD's Conference of the Parties (COP) formally recognized the linkages between biodiversity, food and nutrition, and the need to enhance sustainable use of biodiversity to combat hunger and malnutrition. The COP requested the CBD's Executive Secretary, in collaboration with FAO and the former International Plant Genetic Resources Institute, now Bioversity International, to undertake a cross-cutting initiative on biodiversity for food and nutrition (CBD 2004). Later that same year, the Commission on Genetic Resources for Food and Agriculture (CGRFA) also requested that FAO evaluate the relationship between biodiversity and nutrition. In 2005, via the Intergovernmental Technical Working Group on Plant Genetic Resources for Food and Agriculture, eight high-priority actions and another six lower-priority actions were identified (FAO 2005). In 2006, the COP adopted the Framework for a Cross-Cutting Initiative on Biodiversity for Food and Nutrition (CBD 2006). The Initiative gave a useful profile to some on-going research and development activities, and motivated renewed efforts in establishing and documenting the linkage among agriculture, health and the environment sectors in addressing food and nutrition security with biodiversity as a central feature. For the nutrition, community this represented a major thrust to mainstream biodiversity in nutrition research, projects, programmes and initiatives.

The CGRFA, at its 14th session in 2013 (FAO 2013a), formally recognized nutrients and diets, as well as food, as ecosystem services, in order to further increase the awareness of human nutrition as a concern for the environment sector, and the awareness among human nutritionists of the importance of biodiversity; and requested the preparation of guidelines for mainstreaming biodiversity into all aspects of nutrition, including nutrition education, nutrition interventions, nutrition policies and programmes. These mainstreaming guidelines were adopted at the 15th Session of the CGRFA in 2015 (FAO 2015)[14] to assist countries in mainstreaming biodiversity into different sectors at country and regional levels, and into policies, programmes and plans of action, all with the aim of improving nutrition. Prior to this formalized recognition, similarly important declarations were made, based on collection and analysis of research and traditional knowledge, in order to bring biodiversity and its attendant issues to the forefront of mainstream nutrition thinking. One of these was the AFROFOODS Call for Action (2009). This declaration was motivated in part by the Lancet series (2008), and in part by a prevailing dogma that Africa did not have the affluence or ability to be concerned about biodiversity, or indeed environmental sustainability, as other competing issues took priority (FAO 2009).

The Second International Conference on Nutrition (ICN2), jointly convened by FAO and WHO in 2014, focused on policies aimed at eradicating

[14] http://www.fao.org/3/a-mm464e.pdf

malnutrition in all its forms and transforming food systems to make nutritious diets available to all. Participants at ICN2 endorsed the Rome Declaration on Nutrition[15] and the Framework for Action[16]. While the ICN2 outcomes do not explicitly mention the potential use of biodiversity or genetic resources for food and agriculture to address malnutrition, some recommendations are highly relevant to promoting the use of biodiversity to address certain nutritional problems. Examples include the following:

- Recommendation 8 on the need to "review national policies and investments and integrate nutrition objectives into food and agriculture policy, programme design and implementation, to enhance nutrition sensitive agriculture[17], ensure food security and enable healthy diets".

- Recommendation 10 on the need to "promote the diversification of crops including underutilized traditional crops, more production of fruits and vegetables, and appropriate production of animal-source products as needed, applying sustainable food production and natural resource management practices".

- Recommendation 42 on the need to "improve intake of micronutrients through consumption of nutrient-dense foods, especially foods rich in iron, where necessary, through fortification and supplementation strategies, and promote healthy and diversified diets".

11. Ways forward: toward a post-2015 development agenda

Food and nutrition insecurity presents a serious and growing global challenge, as does environmental sustainability, and unsustainable and unhealthy food systems. They affect citizens in all countries, everywhere. They are multifaceted and complex issues, with no single way, or single sector, to effectively solve such problems. Interdisciplinary analysis and cross-sectoral collaboration have been largely absent, with each sector promoting solutions that unleash actual and potential damage to other sectors (McEwan et al. 2013). Examples include agricultural production intensification that causes biodiversity loss (IUCN 2008), food and nutrition interventions that undermine traditional/local agriculture (Frison et al. 2006; Wahlqvist and Specht 1998), and environmental conservation programmes that lead to undernutrition (Kaimowitz and Sheil 2007). While there has been some convergence among the agriculture, environment, health and nutrition communities toward understanding the interdependence between human and ecosystem health, and how agricultural biodiversity and healthy food systems plays a role in maintaining both, more collaboration is needed to simultaneously address the issues and minimize the damage that can arise when sectors work alone (McEwan et al. 2013; Burlingame 2014).

Policy dialogue is also key. Many voices from UN agencies, civil society, academia and the private sector have expressed the need to include biodiversity for food and nutrition in the negotiations for the post-2015 Development Agenda. Calls for Action, Declarations, Recommendations, Codes and Compacts have been put forward to assist the research and development communities in their efforts to address biodiversity for food and nutrition. The draft proposal of the Open Working Group for Sustainable Development Goals presents nutrition together with sustainable agriculture as one goal, and halting biodiversity loss together with protection and sustainable use of ecosystems as another goal (UN 2014). While negotiations on this process are still ongoing, the points raised here are key to informing the critical policy dialogue that is taking place and indeed to the subsequent implementation of the SDGs.

Biodiversity sits at the nexus of improving nutrition and environmental sustainability, and offers unique opportunities to create synergies

[15] http://www.fao.org/3/a-ml542e.pdf

[16] http://www.fao.org/3/a-mm215e.pdf

[17] http://www.fao.org/nutrition/policies-programmes/en/

between human and environmental health. This chapter has reviewed many of the issues pertinent to this and points to a number of areas of concern, which if improved and strengthened can help to improve the contribution of biodiversity to nutrition and human health. These include the following:

1. The current agricultural focus on food quantity requires a paradigm shift to look at ways in which we can maximize food quality and safety. Biodiversity has an important role to play in this. This has many aspects to it, including improving relevant agricultural, trade and food policies. Topical initiatives such as the current interest in nutrition-sensitive agriculture and value chains provide opportunities for biodiversity to contribute to the quality and diversity of agricultural production. Regardless of the many successes of agriculture during the past several decades, it is clear that current methods and levels of food production and consumption are not sustainable, and the finite natural resources of the planet are being exhausted or lost in the process. While agricultural production is theoretically able to feed the world's population, serious malnutrition still persists with an ever increasing diet-related NCD burden, which is going to have major public health cost implications for many countries.

2. If we are to effect such a paradigm shift, moving from a focus on quantity to quality, significant knowledge gaps in our understanding of food biodiversity and its role in improving nutrition, which still remain, will need to be addressed. Among these gaps are: the need for enhanced generation, compilation and dissemination of more food composition data – we still know so little about the nutrient composition of the vast majority of the world's edible biodiversity; the need for whole diets and landscape approaches rather than approaches that focus on specific nutrients or single food approaches; the need for better and more informative research and studies to understand the complex pathways that link biodiversity to human nutrition and health as well as the development of better tools, such as cost of diets and linear programming, and metrics that help us characterize food systems' and ecosystems' ability to provide sustainable diets; we need more information on tested and proven good practices and interventions that can be scaled up to better mobilize biodiversity to improve nutrition. Addressing these gaps would go a long way in creating a more solid scientific base of reliable evidence that acknowledges food biodiversity's actual and potential role in reducing malnutrition.

3. To benefit from a more improved scientific evidence base of this nature, truly interdisciplinary analysis and cross-sectoral collaboration at the highest level will be essential to ensure the effective mainstreaming of biodiversity into relevant policies, programmes and national and regional plans of action on food and nutrition security. This will require transformative political will, leadership and vision. It will also require considerable resources and budgets. While there has been some convergence between the agriculture, environment, health and nutrition communities toward understanding the interdependence between human and ecosystem health, and how biodiversity plays a role in maintaining both, much more is needed to yield the necessary interdisciplinary analysis and cross-sectoral approaches required to better understand and address nutrition and environmental sustainability. In addition, much more is needed to translate recent policy gains and achievements at the global level to action and implementation at country level.

4. All these changes, shifts and transformations will require major attention to improving awareness and understanding among many actors and stakeholders. It will also require significant attention to capacity building at the global, national and local levels. It will require working with universities to encourage the necessary interdisciplinary approaches to teaching and research. Realizing the creation of a scientific evidence base as elaborated above will require major changes in approaches to how we undertake research. It will require

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novel, innovative ways for individuals, disciplines and organizations to work together. It will also require efforts aimed at increasing the awareness of the general public, policy-makers, decision-makers and of the different stakeholders across all sectors on the importance of foods from different varieties and breeds of plants and animals, as well as wild, neglected and underutilized species, in addressing malnutrition.

5. All of this presents a big agenda; however, the post-2015 Development Agenda presents a big opportunity. As we move forward into the post-2015 Development Agenda we find ourselves on the threshold of an opportunity where humanity can decide to alter course and move beyond business-as-usual, which is really no longer viable, to scenarios that facilitate real substantial transformative change. As we have seen, the challenges of the twenty-first century are increasingly interconnected. The challenge of achieving good nutrition status in a way that is environmentally sustainable is only now beginning to receive serious attention. A change at scale in how people interact with their environment to fulfil the goals of food and nutrition security is required. As we move forward into the post-2015 Development Agenda, it is increasingly recognized that human nutrition and environmental sustainability should be considered intrinsically linked. But a major question now is "how to practically do so?'. This chapter has gone some way in addressing this question. Innovative scientific methods, pilot studies, metrics and good practices are emerging to help us rise to the challenge. The opportunity is now to ensure that nutrition security and environment are closely linked through biodiversity in the post-2015 Agenda.

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7. Infectious diseases

1. Introduction and background

1.1 Introduction

Infectious diseases have important implications for both human health and biodiversity. Pathogens, the infectious diseases they cause, and the organisms that carry them are often recognized for their detrimental effects, but also serve vital roles for some species, ecosystem functioning and supporting biodiversity. The same microbe may be pathogenic to some hosts and beneficial to others, and the diversity and interactions of microbes are important. For example, commensal organisms (normal microbial flora) serve an important role in fighting pathogens. This essential complexity is often best understood in the plant kingdom, with well-documented interdependencies among plant species and microbes. In some cases, public health and biodiversity needs do not align and must be balanced. However, human-caused global changes, such as deforestation, extractive industries including logging and mining, introduction of invasive species, and urban development, are driving infectious disease emergence and spread, as well as biodiversity loss. There are opportunities for preventing infectious diseases *and* reducing biodiversity loss by addressing their common drivers through a synergistic approach.

1.2 Socioecological relevance and impacts of infectious diseases

Endemic infectious diseases (those that have been stably established in a given region) are responsible for over one billion human cases per year, leading to millions of deaths annually (Grace et al. 2006). Two-thirds of known human infectious pathogens have emerged from animals, with the majority of recently emerging pathogens originating in wildlife (Taylor et al. 2001; Jones et al. 2008). This transmission from other species to humans fits with pathogen ecology and evolution (e.g. opportunistic microbial adaptation and niche exploitation), but our increasing interactions with the environment are enabling opportunities for pathogen spill-over into humans and altering the systems around pathogen evolution and survival (Karesh et al. 2012). The human–human transmission potential varies among pathogens. For example, some infections are established in animals (enzootic) and can be transmitted to people, but typically do not transmit between people (e.g. rabies), whereas others may be maintained in human populations primarily by human–human transmission following initial infection (e.g. HIV and Ebola virus disease).

With global change, ecological determinants are interfacing more and more with socioeconomic dynamics, affecting disease risks. As the global population increases, over five billion people are projected to be living in urban areas by 2030, and land allocated to urban landscapes is expected to triple from 2000 levels (Seto et al. 2012), posing growing resource demands. Urban demography presents variable socioeconomic trends, with a significant population globally (≥800 million people) residing in urban slums, with limited access to sustaining resources and sanitation (Hacker et al. 2013). While the risks and impacts of infectious diseases are not limited to urban settings, urban conditions may present heightened potential for spread and maintenance in population-dense settings.

In addition to the burden of human morbidity and mortality, there are high financial costs associated with infectious diseases. For example, the 2003 SARS outbreak was estimated to cost the global economy over US $30 billion. Regionally endemic, often "neglected" diseases also inflict economic damages, e.g. control and treatment for the canine tapeworm-transmitted *Echinoccocus* – for which ungulates serve as an intermediate host – totals over US $4 billion annually. Whereas emerging diseases may pose acute health and financial impacts, they may potentially become endemic, posing long-term impacts. Vector-borne and parasitic diseases, for which the predicted disease burden is driven by biodiversity changes (increasing as biodiversity declines), have been shown to amplify the poverty cycle in some areas (Bonds et al. 2012).

1.3 Ecological background

Ecologists have observed that animal populations may contain significant numbers of infected animals with few ecological consequences, e.g. healthy pinniped and grouse population dynamics are influenced by the frequency and severity of epidemics without necessarily causing long-term decline (Harwood & Hall 1990; Hudson et al. 1998). On the other hand, the ecology of an ecosystem (for example, factors including its function and structure) can be fundamentally changed by disease alone. The introduction of the rinderpest virus has dramatically altered the animal and plant ecology of the Serengeti ecosystem with impacts visible over a century later (Holdo et al. 2007). At a micro-level, the shared evolutionary fate of humans and their symbiotic bacteria has selected for mutual interactions that are essential for human health, and ecological or genetic changes that uncouple this shared fate can result in disease (Dethlefsen et al. 2007). Geneticists have added a further layer of understanding on the role disease plays in maintaining the genetic diversity or variation within populations (Acevedo-Whitehouse et al. 2005; Acevedo-Whitehouse et al. 2006). Humans have generally worked to disrupt or deny this process in both our own species by disease control efforts, and in animals through both selective breeding and disease control (see also chapter on microbial communities within this volume).

Despite our disease control efforts, there is increasing evidence that susceptibility to disease has genetic determinants, as shown in bovines (Richards et al. 2010; Driscoll et al. 2011). The assumption from these results is that disease (through parasitic and/or pathogenic mechanisms) contributes to maintaining genetic health, through "selecting" and "removing" the more homozygous, disease-susceptible individuals and their genes (Acevedo-Whitehouse et al. 2003; Luquet et al. 2012; Paterson et al. 1998; Amos et al. 2009). Disease may also play a role in selection of animals for predation through reducing their fitness and this in turn may determine evolutionary polymorphism and strain diversity of the infective agents and/or pathogens adapted to these hosts (Morozov 2012). Disease ecology of natural populations is complex and there is probably considerable fine tuning at the level of the host, pathogen and the environment, also considering co-infection (Ezenwa and Jolles 2011; Cleaveland et al. 2008) and predation effects (Hethcotea et al 2004). With some pathogens, e.g. trypanosomes and avian influenza viruses, the regular challenge they present to the immune system in a wide range of hosts induces rapid evolution of new antigenic profiles in parasite populations, as well as a strong selection pressure for heterozygosity and/or variability in the parasite population. The host community responds with adaptive immunity and latent infection, and with sub-clinical disease at worst when stressed (Huchzmeyer 2001; van Gils et al. 2007). These findings suggest that an ecological approach to disease, rather than a simplistic "one germ, one disease" approach will provide a richer understanding of disease-related outcomes.

2. Infectious disease ecology and drivers

2.1 The complex relationship between habitat, biodiversity and disease

Anthropogenic disturbance and biodiversity loss have been strongly linked to increased prevalence and elevated risk of zoonotic disease for a variety of pathogens. For instance, hantavirus prevalence is thought to increase when mammal diversity decreases; the rise of West Nile virus is correlated with decreases in non-passerine bird richness; landscape prevalence of *Bartonella* increases when large wildlife are removed; and habitat fragmentation increases risk of Lyme disease (Allan et al. 2003; Ezenwa et al. 2006; Suzán et al. 2009; Young et al. 2014). Given that more than 60% of described human infectious diseases are zoonotic (Taylor et al. 2001), including many of humanity's most pervasive diseases (e.g. influenza, schistosomiasis), the relationships between biodiversity loss, disturbance and disease will have enormous consequences for human well-being.

Changing landscape patterns can both positively and negatively affect the transmission of zoonotic disease depending on the habitat change, shifts in species composition and the resulting extent of human–disease contact (Rapport et al. 2009). In many areas, human-induced land use changes are primary drivers of range of infectious disease outbreaks and emergence events and modifiers of transmission of endemic infections (Patz et al. 2000). Indeed, land use change, food production and agricultural change are reported to collectively account for almost half of all global zoonotic emergent infectious diseases (Keesing et al. 2010). At this scale, the most important factors may be the contact among people and wildlife that harbour zoonotic pathogens. For example, pristine forests in West Africa harbour bats that carry Ebola virus, but anthropogenic land use change, beginning with logging roads, bushmeat hunting, development of villages and transformation for agriculture, likely brings human populations into closer contact with the reservoir hosts (Walsh et al. 2003).

Natural landscapes also harbour vectors of human pathogens, some of which have thwarted the colonization and persistence of human settlements in some regions. In particular, malaria, carried and transmitted by the *Anopheles sp*. mosquito, has plagued human populations globally for centuries. The drainage of large areas of wetland and swamps, the breeding habitat for *Anopheles sp*., for agriculture and land use change has helped to dramatically reduce the incidence of malaria in some parts of the world (e.g. Lower Great Lakes Basin, Rapport et al 2009). Meanwhile, deforestation has coincided with an upsurge of malaria and its vectors in Africa (Coluzzi 1984; Coluzzi 1994; Coluzzi et al. 1979), in Asia (Bunnag et al. 1979) and in Latin America (Tadei et al. 1998) as converted lands often include more areas of still water necessary for breeding of malaria-transmitting mosquitos than intact forest (Charlwood and Alecrim 1989; Marquez 1987). This is especially true with expansion of paddy-field rice cultivation in previously forested areas, creating substantial habitat areas for the mosquito (Singh et al. 1989). In Africa, the extensive current deforestation and expansion of human activities into previously untouched regions is increasing direct or indirect contact between humans and the natural reservoirs of diseases, linked to increases in Yellow Fever (Brown 1977), and leishmaniasis (Sutherst 1993).

The mechanisms by which these relationships occur vary by systems, and include changes in host density, host behaviour, and mean competence of all the hosts in an ecosystem at maintaining and transmitting a pathogen (Keesing et al. 2006). However, much of the focus on the diversity–disease relationship to date has focused on one particular mechanism – the so called "dilution effect." The dilution effect suggests that non-random patterns of biodiversity loss following human disturbance will cause systematic losses of low competence ("diluting") hosts, thereby increasing mean competence of hosts, and causing an overall increased prevalence of pathogens in a landscape (Ostfeld and Keesing 2012; Myers et al. 2013). This pattern is hypothesized to occur because of a correlation between "pace of life", competence and vulnerability to human disturbance. Consistent with this, there are now several studies that have found that fast life history traits also favour high host competence (Johnson et al. 2012; Johnson et al. 2013a; Joseph et al. 2013), likely mediated by variation in immunological tolerance (Previtali et al. 2012). Direct links between susceptibility to human disturbance and mean competence for a particular pathogen have also been found in a few disease systems (Johnson et al. 2013b). While the dilution theory has been proposed as the mechanism for some specific circumstances (e.g. tick-borne disease), the effect appears to be more dependent on community composition rather than biodiversity itself, and has been the subject of significant debate in the literature (e.g. Randolph and Dobson 2012).

Thus, the impacts of biodiversity loss and habitat disturbance are far from straightforward, linear or consistent (Ostfeld and Keesing 2012; Wood et al. 2014). Even for a single disease, such as Lyme disease or malaria, the magnitude and direction of impact can vary across environmental contexts and scales (Swei et al. 2011; Valle and Clark 2013; Wood and Lafferty 2013), and quantitative reviews across pathogens and systems have also shown even more mixed effects (Salkeld et al. 2013; Young et al. 2013). Most of the theoretical and experimental work to date on the dilution effect focuses on a small subset of vector-borne diseases that meet a series of strict criteria; careful review of major human pathogens suggests that only a subset appear likely to meet all criteria that would make such a relationship likely (Wood et al. 2014). Parasite biodiversity and human pathogen richness also covary with diversity of larger animals (Dunn et al. 2010), driving an increased risk of emergence of novel infectious disease from biodiversity hotspots (Jones et al. 2008). Moreover, anthropogenic disturbance is not always, or even typically, associated with changes in diversity or species richness *per se*, but rather with changes in community composition (Dornelas et al. 2014). Changing species and population dynamics may also cause the amplification of a disease, enabling more efficient transmission and spread.

There is a strong and pressing need for more research on both the mechanisms and context dependence of disturbance–biodiversity–disease relationships – recognizing that diversity–disease relationships are likely to vary with both space and time. While negative disturbance–disease relationships certainly occur, we do not yet have strong predictive power to suggest when and where they will occur for most human pathogens. Environmental characteristics are also strongly likely to impact the likelihood of feedback between disturbance and disease prevalence (Estrada-Peña et al. 2014), but the nature of these relationships are still poorly understood.

2.2 Biodiversity and hotspots of diseases

Disease and biodiversity links can also be viewed on a more global scale. In a 2008 study, Jones et al. analysed the distribution of emerging infectious disease (EID) events, defined as "the first temporal emergence of a pathogen in a human population... related to the increase in distribution, increase in incidence or increase in virulence or other factor which led to that pathogen being classed as an emerging disease" (Jones et al. 2008). Jones et al. found that, after correcting for reporting bias, EID events for different classes of diseases had different global distributions (thus allowing us to see so-called "hotspots" of disease emergence). Jones et al. also examined the association of EID events with different socioeconomic and environmental drivers of disease emergence, including mammal species richness. They found that mammalian biodiversity was a significant predictor of the origin of zoonoses from wildlife.

These findings suggest that biodiversity contributes to disease emergence risk. One potential mechanism for this is that areas with high biodiversity may play host to a larger pool of pathogens with the potential to infect humans

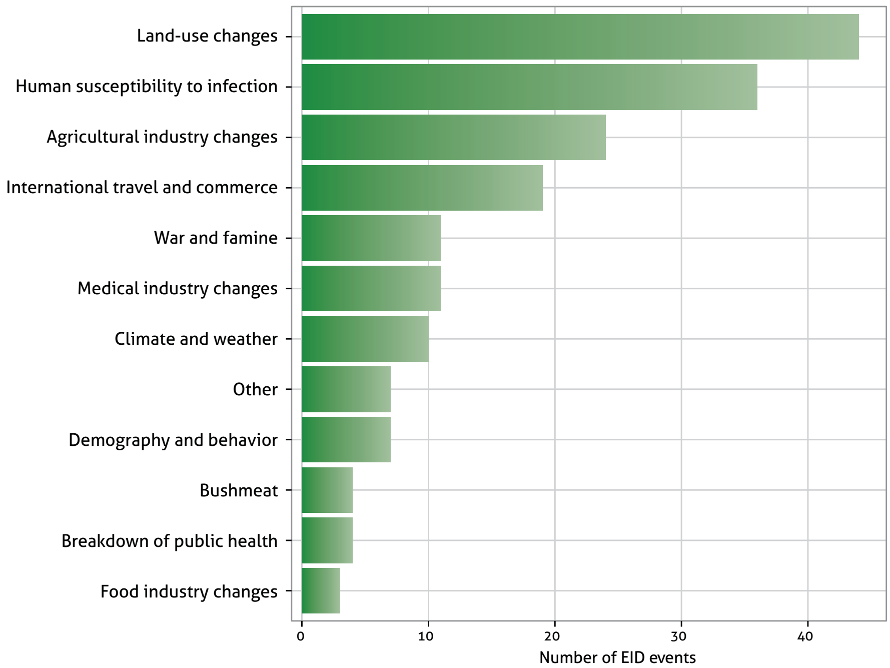
(Murray & Daszak 2013). If we assume that each animal species is host to an average number of pathogen species, we would expect regions with more animal species to also contain more species of pathogens. If a relatively fixed proportion of pathogens were able to infect humans, then we would expect to see more emerging zoonoses in those regions. However, evidence supporting this assumption is scant; pathogen diversity and the ability of a pathogen to infect humans seem to differ between taxa (Murray & Daszak 2013; Ostfeld & Keesing 2013). Further study of the ecology of host and pathogen biodiversity would deepen our understanding of the role that biodiversity plays in the risk of disease emergence. This is especially warranted given the rapidly changing ecological dynamics that are driving infectious disease emergence.

2.3 Implications of ecosystem and land use change: drivers of infectious diseases

During the last half century, anthropogenic conversion of much of the Earth's natural ecosystems has greatly increased. Significant changes in land use are occurring currently, mainly in developing, tropical forest countries (Lambin and Meyfroidt 2011). It is estimated that annual forest loss has averaged 2101km²/year across the tropics between 2000 and 2012, and is increasing globally (Hansen et al. 2013). Much of this forest loss can be attributed to growing global demand for food and natural resources (Cohen 2003; DeFries et al. 2010). In extent, the most significant form of land-use change is the expansion of crop and pastoral lands, which continue to have serious negative long-term consequences for conservation of global biodiversity (Phalan et al. 2013), as agricultural expansion has largely come at the expense of intact forests (Gibbs et al. 2010; Lambin and Meyfroidt 2011).

Under land-use change, human activities have the potential to impact disease dynamics by directly and indirectly changing the behaviour, distribution, abundance and contact between host species and vectors, as well as altering host community composition. Land-use change has been identified as a leading driver of recently-emerging infectious diseases in humans (Figure 1). Common land-use changes related to disease transmission include agricultural development, urbanization, deforestation, and forest and habitat

FIGURE 1: Drivers of emerging infectious diseases from wildlife (Loh et al., Vector Borne and Zoonotic Diseases. In press)



fragmentation. A recent review investigating how specific types of land-use change influence infectious disease risk found that more than half of the studies (56.9%) documented increased pathogen transmission, 10.4% of studies observed decreased pathogen transmission, 30.4% had variable and complex pathogen responses, and 2.4% showed no detectable changes (Gottdenker et al. 2014).

Despite numerous and increasing attempts to detect a general relationship between land-use change, biodiversity and disease risk, studies to date suggest few generalizations. As noted in the sections above, a growing number of studies have shown that biodiversity can influence disease risk through: 1) an "amplification effect" that predicts a positive correlation between biodiversity and disease risk; or 2) via a "dilution effect" in which one would expect biodiversity to negatively correlate with disease risk (Dunn 2010; Keesing et al. 2010). Yet, examination of the theoretical and empirical evidence has produced mixed support as to which of these hypotheses is generally more likely to occur under a land-use change scenario (Brearley et al. 2012; Murray and Daszak 2013; Randolph and Dobson 2012; Vourc'h et al. 2012).

2.3.1 Extractive industries

Disease impacts may be magnified in tropical regions where primary forest is opened up to mining, logging, plantation development, or oil and gas extraction (Karesh et al. 2012). These factors have been associated with outbreaks of Marburg virus, Chagas disease, yellow fever, leishmaniasis and others.

Box 1: Case study: Changing human–animal–environment dynamics and the emergence of Nipah virus

Increasingly intensified human-caused landscape and behaviour changes have had significant consequences for human health over past decades. The emergence of Nipah virus provides a useful example of anthropogenic drivers of EIDs. In 1998, the Nipah virus outbreak emerged in humans in Malaysia. Flying fox bats (*Pteropus* spp.), the natural reservoir for Nipah virus, had first infected domestic pigs. The vehicle for the bat–pig spillover is thought to be fruit contaminated with bat saliva from a fruit tree on the pig farm (Daszak et al. 2013). The dense pig housing conditions, respiratory shedding and high birth rate enabled "amplification" of viral transmission, allowing ease of transmission between pigs and to humans, leading to encephalitis and respiratory disease and over 100 human deaths. The disease was also seen in Singapore and was estimated to cost US$550–650 million in South East Asia, including costs incurred for control measures, the financial impact to swine industry, and loss of employment (Newcomb et al. 2011). Nipah virus has also since emerged in Bangladesh and caused upwards of ten human outbreaks since 2001 (Luby et al. 2009a). The primary mode of the initial transmission to humans in these outbreaks is thought to be infection directly via ingestion of date palm sap that has been contaminated with bat saliva, urine or faeces (human–human transmission following initial infection has also been reported in Bangladesh's Nipah virus outbreaks) (Luby et al 2009a; Luby et al. 2009b). Domestic animals may also consume the date palm sap contaminated by bats, thus potentially becoming infected and serving as an intermediate host for infection to humans or other species (Hughes et al. 2009). As a preventive solution, some date palm sap harvesters and researchers have tried placing bamboo skirts over sap collection buckets to protect the harvest from contamination (Luby et al. 2009a; Khan et al. 2012). This approach promotes both human livelihoods and the continued ecosystem services provided by bats such as seed dispersion and pollination (Luby et al. 2009b).

The situations by which Nipah virus has emerged and re-emerged demonstrate two key factors: 1) Human activity has driven Nipah virus emergence events. In Malaysia, deforestation and intensified agriculture enabled the movement and mixing of species and the resulting opportunity for pathogen transmission. In Bangladesh, human demand for natural resources through tapping into trees for sap enabled a new food source for bats, similarly providing pathogen mixing opportunities that can be detrimental to people and domestic animals (and potentially wildlife through conflict with humans given health and livelihood risks, though this has not been documented specifically for Nipah virus). 2) Ecosystem dynamics and disease ecology are complex. Land-use change and other changing ecological scenarios in one region may have unanticipated effects in another region through species range adaptations and other factors. Climate change scenario models have suggested that increasing temperature may enable spread of the bat species that harbour Nipah virus (Daszak et al. 2013). Valuable information on risk factors for transmission from bats has been gained from bat ecology studies, such as considerations around seroprevalence for Nipah virus, bat mobility and colony connectivity, and temporal/seasonal aspects (Rahman et al. 2013). An ecosystem health perspective is needed to better understand and mitigate both health and biodiversity risks of potential changes to the environment.

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Box 2: Ecological dynamics of infectious Disease: examples from South America

Changes in species biodiversity and composition affect infectious disease transmission dynamics (Terborgh et al. 2001; Osteld & Holt; 2004, Rocha et al.; 2014). In the Brazilian Amazon, the transmission cycle for the human Chagas disease-causing parasite, *Trypanosona cruzi*, is related to changes in small mammal composition. Species competent in transmission have been favoured by transformation of native forest for homogeneous açaí plantations. The vector (*Hemiptera* sp.) is sheltered naturally in palm trees and is attracted to açaí plantations. As major wild mammals have been removed from these areas, the vector is attracted to human habitations and begins to feed on people and domestic animals living or working at açaí plantations, thus transposing the sylvatic cycle to human dwellings (Araújo et al. 2009; Varella et al. 2009; Xavier et al. 2012). Handling, extraction and preparation of coconut açaí pulp can allow for oral transmission (via contaminated food) of *T. cruzi*, as the vector can be crushed in açaí processing and remains in cold conditions until consumption, resulting in more than 100 new registered cases annually (Ministério da Saúde 2005; Roque et al. 2008; Nobrega et al. 2009). The costs of Chagas disease are high: 30% of infected people develop serious heart and digestive diseases. From 1975 to 1995 the Brazil Government invested US$ 420 million in control of Chagas disease, with a return of US$ 3 billion, or US$ 7.16 for each dollar invested (Akhavan 2000). Similar ecological dynamics have been observed for spotted fever, an acute infection caused by the bacterium *Rickettsia rickettsii*, and transmitted by the bite of an infected tick. Incidence in Brazil has been increasing since 1996, although most cases are not diagnosed. Human mortality rate is 20%, and the most common vector is the star tick, *Amblyomma cajennense,* that typically infests chickens, horses, cattle, dogs and pigs, as well as wild animals such as capybaras, opossums, armadillos, snakes and wild canids. Changing species composition in small fragments and conservation units remaining around the Atlantic Forest have resulted in growing cases in south eastern Brazil, as also seen with Lyme disease in the United States (Meira et al. 2013).

Some disease relationships involve predator and prey, as predators can feed on prey that were already ill or disabled, removing them from a population and thus controlling disease. Other dynamics may also play important roles, as seen with the increase in rodent populations that are controlled by a combination of factors besides predator control (Mills 2006; Armién et al. 2009), as seems to be the scenario for hantavirus in the southern cone of South America. Several rodent species and viral genotypes build a parasite–host puzzle in which hantavirus infection is density-dependent of rodent populations. Rodent populations are promoted by food supply, absence of predators, and even adaptability to synanthropic surroundings (Palma et al. 2012). In this region, habitat characteristics determine infection prevalence. In Paraguay and Uruguay, the highest prevalence of infected rodents are in disturbed areas such as planted fields, highway boundaries, planted forests, shrub-woods and near houses. In these cases, predators no longer exist and even with depleted populations of rodents, some population densities are high, increasing transmission risk. In Argentina, areas with highest prevalence are the preserved ones, demonstrating complexities and showing that knowledge of species and habitat characteristics are fundamental to the study of disease (Palma et al. 2012).

In the Amazon region the number of cases of human bat bites increased by nine times in areas of greatest deforestation between the years 2003 (852 cases) and 2004 (8,258 cases) (Ministério da Saúde 2006). In Pará, the Brazilian state with the highest deforestation rate, the number of cases jumped from 383 in 2003, to 7,640 in 2004, and more than 15,000 cases in 2005. These and other increases have been related to the loss of the wild native species that are the natural food sources for blood-sucking bats; humans, especially in mining areas, may serve as a substitute. Despite an increase in the number of bites, a decrease in the number of rabies cases was observed, likely indicating development of immunity in human populations through repeated exposure (Schneider et al. 2001).

Ecological studies in the Amazon correlate deforestation, hydroelectric industry, human occupations, and the presence of the mosquito vector *Anopheles darlingi* with increased malaria risk (Vasconcelos et al. 2006; Vittor et al. 2009). In regions with large hydropower plants, the rate of malaria is 278 times higher than in forested areas (Afrane et al. 2006). In Brazil, according to 2011 data from the Ministry of Health, 99.5% of cases of disease transmission were in the Amazon region. In Amazonia, a complex set of factors relate disease transmission with environmental transformation. High mosquito density caused by deforestation, construction of power plants, roads, irrigation, dams and the large influx of susceptible people (often living in houses without walls) inside or in forest edges helps increase circulation of aetiological agents linked to geographical and climatic factors such as high rates of rainfall, watershed amplitude and vegetation cover (Oliveira-Ferreira et al. 2010).

Genetic erosion may occur with loss of species, resulting in selection of receptive individuals for new pathogens or ones without ability to adapt to growing resistance to pathogens already present. This creates patches of high prevalence of infection and risk of spill-over to neighbouring regions, signifying the need to align conservation and health goals to maintain connectivity between natural areas to reduce anthropogenic driving forces for the emergence of diseases and biodiversity loss.

Disease dynamics are not limited to terrestrial settings. In marine environments, parasites tend to be generalists that seemingly use an adaptive strategy of dispersion in fluid environments. Infective forms of parasites are more common on juvenile fishes that are transmitted to others through the food chain by predation (Marcogliese 2002). In some cases, humans can replace natural definitive hosts (e.g. cetaceans and pinnipeds) by eating raw fish. Thus, the reduction of fish stocks and the size of fish caught (Shin et al. 2005) may be risk factors for helminth transmission (Ferreira et al 1984). Oceans are typically a final destination for effluent of domestic and industrial activities, and high concentrations of microbes in coastal waters indicate probable water and seafood contamination. Many bacteria and viruses are autochthonous to marine ecosystems (e.g. *Aeromonadaceae* and *Vibrionaceae*), so the use of enteric microbes as indicators of microbiological water quality is strongly limited, although many of them are clinically important to human health and biodiversity (Moura et al. 2012). Early eutrophication of aquatic systems benefits parasites with gastropod and crustacean secondary hosts; additionally, release of waste into rivers and seas from human sewage and animal farms also increases blackfly populations, resulting in increased risk of transmission of onchocerciasis and economic losses to the cattle industry in areas of the Atlantic forest (Strieder et al. 2009).

Taken together, these examples of different infectious disease scenarios observed in South America highlight the complexity of disease ecology, and the impacts of rapidly changing environmental pressures. Ultimately, they demonstrate the importance of employing science-based proactive disease risk analyses and risk prevention and mitigation strategies.

The mechanisms vary among sites and extractive activity, but road building, establishment of settlements, and increased mobility of people into remote regions, coupled with a lack of domestic animal food supply likely lead to an increase in hunting, wildlife consumption, and wildlife trade in areas where these changes are occurring. Further, if sites are poorly managed, increased populations can strain existing infrastructure, leading to overcrowding, poor sanitary conditions, improper disposal of waste, and a lack of potable water. All of these changes increase the risk of cross-species transmission of pathogens, which can result in zoonotic disease. Additionally, new human inhabitants (recent immigrants) might not have immunity to zoonotic diseases endemic to the area, making them particularly susceptible to infection.

2.3.2 Food production

Changing food production methods, particularly in livestock production, to meet the protein needs of a growing global population have also increased contact and pathogen transmission opportunities between domestic animals, wildlife and humans. Livestock grazing and livestock-associated feed crops account for an estimated 30% of land area use, commonly involving deforestation for cattle farming (Pinto et al. 2008). The resulting infectious disease dynamics have ecological risks relevant to biodiversity, especially as areas may be located on the perimeter of forest, wetlands and other natural areas where wildlife–livestock animal contact opportunities are heightened. The intensification of livestock production in many parts of the world, typically involving high animal density, confined living quarters, and antimicrobial use, have created conditions that may enable rapid pathogen spread and evolution, especially among genetically similar breeds or immune-suppressed animals (Liverani et al. 2013). The introduction of disease can occur through many pathways, including from wildlife (e.g. via direct contact, via a vector carrying a pathogen acquired from wildlife, etc.). Wildlife may serve as reservoirs or hosts for diseases of high importance for livestock production, including the majority of those listed by the World Organisation for Animal Health (OIE), such as the causal agents for foot and mouth disease and bovine tuberculosis (Cleaveland et al. 2005; Miller et al. 2013). Non-zoonotic diseases, while not posing infection risks to humans or wildlife, can have detrimental impacts on food security and thus access to nutrition for human populations.

In addition to threats to livelihoods and food security from livestock die-offs, human health may be impacted. Livestock may serve as intermediate hosts for zoonotic disease transmission from wildlife to humans, in some cases serving an amplifying role. For example, Nipah virus, for which fruit bats are a natural reservoir, emerged in humans in Malaysia following conversion of forest to an intensive swine facility that enabled bat–swine contact, and subsequently transmission from pigs to humans (Karesh et al. 2012).

Most directly related to biodiversity, although less well established given limited wildlife disease surveillance, are known and novel pathogen transmission events to wildlife from livestock or humans (Messenger et al. 2014). Epizootics of rinderpest, a cattle disease, have caused large wildlife die-offs (Domenech et al. 2009). Smallholder farming, primarily in low- to middle-income, often biodiversity-rich areas in the southern hemisphere presents ongoing opportunities for contact between wildlife and domestic animals. As seen in southern Africa, the co-evolution in wildlife and livestock for several pathogens presents complex disease risks (Cleaveland et al. 2005; Thomson et al. 2013). Biosecurity strategies may not be available, or are ineffective. In some cases, disease containment measures in food production may pose direct threats to biodiversity; for example, fencing used to enclose livestock production sites may cause detrimental fragmentation of wildlife population, affecting genetic diversity and increasing risk of population crashes (Thomson et al. 2013).

Non-therapeutic use of antimicrobials in food production systems (both agriculture and aquaculture) for prophylaxis and growth promotion may also pose implications for biodiversity and potentially human medicine. While development of antimicrobial resistance

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is a natural phenomenon, the widespread of use of antimicrobials can create genetic selection pressures for resistant strains. Dispersion of antimicrobial drugs as well as genetic exchange through ecological processes may also present non-target environmental exposure in humans and wildlife (Allen et al. 2010).

2.3.3 Wildlife trade and disease

Trade in wildlife involves the geographic movement of hundreds of millions plants and animals worldwide comprising an estimated economic value of over US$ 300 billion per annum (including both legal and illegal trade estimates) (Ahlenius 2008). This trade is driven by consumer demand for a multitude of products ranging from traditional medicines, bushmeat, trophies, live exotic pets, and foods. Within each of these broad categories exists a wide range of specialty market value chains that vary greatly in their motivating economics, sociocultural origins, geographical source and destination, transportation type and route, trader and consumer profiles, species composition and condition, and local and international legality.

Trade in wildlife is illegal if it is contrary to the laws of the participating nations or the limitations on trade presented by the Convention on International Trade of Endangered Species of Flora and Fauna (CITES). Despite such protections, it is estimated that illegal wildlife trade results in a mean source population decline of 60–70% in targeted species (Karesh et al. 2012). This failure to protect vulnerable populations is a testament to the evasiveness of the wildlife trafficking industry from poacher to the black market, seemingly impossible to monitor, let alone control. Further, challenges in curbing illegal international wildlife trade described by Conrad (2012) include high demand and profit, cultural and societal traditions, ambiguity of property rights, negative economic incentives for bans, and inadequate enforcement. Of additional concern is the fact that only CITES-listed species garner much attempt at regulation at all, while the ecological impact of harvest and international trade of billions of non-CITES-listed animals goes largely unassessed.

The hefty economic value of the global trade in wildlife is rarely countered in the literature by its costs to governments and the public for the introduction of invasive species, as discussed further in the following section. Likewise, several significant zoonotic infectious diseases have emerged in part due to the substantial human–animal contact that occurs along the wildlife trade chain, from harvest to end point. These diseases have included SARS coronavirus (wet markets in China), HIV (primate bushmeat hunting), monkeypox virus (exotic pet trade), and H5N1 and H7N9 avian influenza viruses (Karesh et al. 2005; Gilbert et al. 2014). The global trade in wildlife provides disease transmission mechanisms that not only result in human and animal health threats but also damages to international trade, agricultural livelihoods, and global food security.

There is minimal overall health regulation of the wildlife trade in comparison to agricultural trade, and such work falls between regulatory authorities of national ministries (e.g. agricultural, environmental and public health) and international regulatory organizations. Wildlife trade is complex and multimodal and does not present equal risk to environmental, agricultural and human health. Thus the threat of disease emergence from the wildlife trade and the socioeconomic and behavioural factors that contribute to it cannot be defined with one overarching risk assessment. Rather, specific market value chain types require targeted evaluation and tailored intervention policies that would put measures in place to facilitate relatively benign commerce while establishing the necessary measures to minimize practices that are damaging to the global environment and health.

2.3.4 Implications of biotic exchange (invasive alien species)

The term invasive alien species (IAS) refers to a species, sub-species or other taxon of organism, introduced by human action outside its natural past or present distribution, and whose introduction, establishment and spread threatens biological diversity or ecosystem integrity. Introductions can occur either intentionally or accidentally, and the number of cases has dramatically increased with globalized trade and travel (Butchart et al. 2010). Though many introductions have proven beneficial, the overall impact of IAS on biodiversity as well as on human livelihood is negative, because they threaten health, infrastructures, economic activities, food supplies, and ascetic/cultural ecosystem services (Pejchar and Mooney 2009; Vilà et al. 2010; Stoett 2010). IAS are also implicated in the spread of infectious diseases; and both invasive species and infectious diseases are known drivers of ecosystem change (Crowl et al. 2008).

A recent review (Mazza 2013) suggested that the links between IAS, human health, and infectious disease are manifold. Some pathogens and parasites, such as waterborne cholera or mosquito-borne West Nile virus, can themselves be categorized as IAS. Thus we can view modern pandemics, such as HIV and the SARS crises, as instances of invasion at the microbial level. This application of the IAS category is more usually investigated by epidemiologists than invasion biologists, but the two sciences will continue to learn from each other.

Other IAS act as vectors or reservoirs for pathogens or parasites. For example, the Asian tiger mosquito has been linked to more than 20 diseases, including yellow fever, dengue fever, and chikungunya fever, and climate change projections show that the mosquito will likely extend its range further north in coming years, exposing more people to bites. Raccoon dogs and red foxes are becoming a new reservoir for rabies as they spread into new Eastern European habitats from the accidental release of animals utilized in the fur trade (Mazza 2013; Chomel et al. 2007). The invasion of East Africa by the neotropical shrub *Lantana camara* has increased the incidence of sleeping sickness, since this species provides shelter to the tsetse fly (Mack et al. 2000).

Thirdly, IAS can also influence local conditions, disturbing ecosystems to make them favourable to pathogen or parasitic invasions. The invasion of the North American Great Lakes by the infamous zebra mussel "favours the blooms of toxic cyanobacteria such as *Microcystis aeruginosa* [which] can lead to the accumulation of microcystins, hepatotoxins and probable tumour promoters in the edible tissues of fish and their transfer and magnification along the food chain to final consumers" (Mazza 2013); some reports attribute the rise of Type E botulism in Lake Erie to the ecological impact of the zebra mussel (Perkins et al. 2010). Both the zebra mussel and cholera have been spread by the introduction of discharged ballast water from ships. Cholera killed more than 10 000 people in Peru in 1991, and has been found in ballast tanks from South America in North American ports (Takahashi et al. 2008). Efforts to regulate ballast water have improved vastly in recent years, but it remains a primary vector of IAS worldwide with immediate consequences for human health (see also chapter on freshwater within this volume).

These vector linkages can be quite complex. For example, the water hyacinth, a South American freshwater ornamental plant now introduced worldwide and especially troublesome in sub-Saharan Africa, can host mosquitoes and snail species such as *Biomphalaria sudanica* and *B. choanomphala,* which are in turn vectors of malaria and schistosomiasis (Mack et al. 2000).

Human consumption of plants can also be linked to the spread of disease, since plants themselves are highly susceptible. An analysis of emerging infectious diseases (EIDs) in plants showed that the most significant cause of emergence is pathogen introduction via the international trade in plants and plant materials, as seen with introductions of potato blight in several regions and Moko disease in bananas in Australia (Anderson et al. 2004). Furthermore, the majority of plant EIDs globally over past decades have stemmed from previously unknown pathogens (Santini 2013; see also Bandyopadhyay & Frederiksen 1999; Anderson et al. 2004).

The ecological, health and associated financial costs from invasive alien species introductions are significant. For example, the United States loses an estimated US$ 120 billion per year to the over 50 000 invasive species that have already entered its borders (Pimentel et al. 2005). In most nations these damages go unexamined. Beyond the direct environmental impacts of non-native invasive species lies the less recognized pathogen pollution spread by these hosts. Under-recognized examples abound, ranging from the Varroa mite of pollinating honey bees to crayfish plague (Alderman et al. 1996; Smith et al. 2013).

As climate change proceeds, most projections suggest that there will be a further upsurge in infectious diseases related to IAS (Capinha et al. 2013; Foxcroft et al. 2013; Hatcher et al. 2012) Perkins et al. assert that "[t]he introduction of parasites with invading hosts is the most important driver of disease emergence worldwide" (2010). It is imperative that invasion biology and policy be given adequate resources to recognize and respond to this direct threat to human health. Effective biosecurity policies, focused on prevention of arrival of unwanted IAS, and on properly planned control of the most harmful species, including those potentially impacting human health, can help protect our environments, and also prevent severe impacts on human livelihood. Risk analysis tools, such as stated in the OIE Guidelines for Assessing the Risk of Non-Native Animals Becoming Invasive, can be employed to better manage risks proactively (World Organisation for Animal Health 2012).

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2.3.5 Plant diseases

All biological entities on earth require energy for the construction of their physical structure from molecular components, as well as for movement, behaviour, reproduction and other life activities. The ultimate source of new and replenishing energy is sunlight, but because only green plants and a few algae can capture solar energy and convert it to the "bio-currency" of chemical bonds they are the primary producers in most natural ecosystems, and the rest of us rely upon them, directly or indirectly, for our very lives.

Consideration of biodiversity with respect to plant diseases must include both plants and their pathogens, and in many cases insects that serve as vectors for dissemination of some plant pathogens. Some of the drivers and threats to biodiversity affect all three. For example, ecosystem and land-use changes (such as farming, mining, human habitation, trade and transportation) can change the geographical ranges of plants, microbes and arthropods, creating new community structures and zones of intersection, and increase the risk of the emergence or spread of infectious plant diseases, just as they do in humans and animals. Even programmes designed to manage diseases may threaten biodiversity (Karesh et al. 2012).

Humans depend upon plants for more than just food for ourselves and our livestock; we require their fibre for clothing and shelter, and we are exploring their potential to provide us with renewable sources of biofuels. Over the centuries, humans have utilized well over 7000 plant species, some gathered from nature, but most domesticated and modified via plant breeding for convenient and cost-effective production, harvest and processing. In nations where crops are generally planted as high-yielding monocultures to support modern production technologies, genetic diversity is critical to sustainability in the face of myriad threats (pathogens, insects, weather extremes and climate change, habitat disturbance or loss, escape of genes introduced into crop species, etc.) that could affect a subset of species at any given time. Humans rely currently on only four species, rice, wheat, maize and potatoes, for nearly two-thirds of our food energy requirements.

Genetic diversity within such cultivated species, including progenitors and near-neighbours, is essential for long-term food and fibre security, not only for direct consumption but also as sources of germplasm for cultivar improvement and adaptation in a changing world (FAO 2014; Ingram 2014) (see nutrition chapter).

How does plant diversity influence disease susceptibility and incidence? The answer is: "it depends." There is a non-linear, intricately complex relationship between habitat, biodiversity and diseases, and evidence supports two contrasting hypotheses (Keesing et al. 2006; Pagan et al. 2012). The dilution effect asserts that plant diversity increases the space between individual members of a species, thereby reducing disease risk. Monocultures, being highly artificial environments, drastically alter microclimate habitat and are more susceptible to high losses because if one plant is susceptible, all are susceptible (Pagan et al. 2012; Garrett et al. 2013; Mundt et al. 2002; Zhu et al. 2005). Disease and insect infestations may be less damaging in areas where cropping mixtures (such maize–bean intercropping systems in Latin America, or mixed-cultivar rice crops in China) are still practiced (Castro et al. 1992; Zhu et al. 2005). In the amplification effect, diversity increases disease risk either because it leads to increased abundance of inoculum sources for a focal host (Pagan et al. 2012) or because it considers cases of non-optimal insect vector populations (Keesing et al. 2006). These two hypotheses are not mutually exclusive; rather, they can be considered as the ends of a continuum (Pagan et al. 2012).

Each individual plant supports approximately 30 other species, mostly microbes and insects (Ingram 2014). Many are pathogens, but others are synergists and commensals that fix nitrogen, acquire and share minerals and water from the environment, produce plant growth-promoting substances and antimicrobials, and out-compete harmful organisms. Microbial biodiversity, therefore, is a key factor in plant sustainability, in both natural and managed ecosystems. We know relatively little about microbes that inhabit native plants and how they interact with their hosts, but investigators who look for them rarely fail to find microbes in wild plants; for example, a range of viruses and fungi were detected in asymptomatic grass species in the Tallgrass Prairie of north-central Oklahoma (Dutta et al. 2014; Cox et al. 2013). Can microbes residing in native plants jump to crop species planted nearby? Alternatively, will agricultural pathogens associated with cultivated species escape to wild relatives? Populations of pathogens having multi-species host ranges generally have greater connectedness, and plant community dynamics can change; plant species having greater disease resistance can serve as reservoirs for more susceptible species (Cox et al. 2013).

Aside from its key role in natural settings, microbial biodiversity is also essential for successful agricultural enterprise. "Good" microbes are deployed intentionally into crops for disease biocontrol, nitrogen fixation, plant growth promotion activity, and other benefits. Furthermore, crop improvement efforts, whether by traditional or marker-assisted breeding, or genetic modification, are dependent upon the availability of diverse and relevant pathogen

Box 3: One Health

The growing One Health philosophy provides a new and overarching perspective for understanding the intersections of medicine, veterinary science and the environment (Karesh et al. 2012). Although plant health and pathogen interactions are clearly central to sustainable life on earth, their critical roles in the health of people, animals, and other elements of the environment should be more systematically addressed as science seeks a holistic strategy that enfolds the multisectoral, policy-level approaches that promote a One Health perspective (Fletcher et al. 2009).

strains for cultivar screening and evaluation of disease resistance.

2.3.6 Marine infectious disease

Infectious diseases are important drivers within ecosystems, including marine ecosystems. Marine infectious disease is a complex interaction between the host, pathogen and the environment (reviewed by Burge et al. 2014), and each host–pathogen interaction should be considered in a case-by-case manner. The ocean is a complex human-coupled environment where transmission and severity of disease can be impacted by terrestrial run-off and pollution, direct and indirect impacts of climate change, transfers of animals (culture, aquarium trade and private citizens), fishing and aquaculture. Although disease is a notable driver of community change in marine ecosystems, we still lack baseline data and understanding of transmission dynamics in many systems. The presence of disease is often first noted by dramatic large-scale die-offs of organisms. In case studies spanning the globe, including both temperate and tropical systems, diseases have been found to be important drivers of marine biodiversity change. Key examples of large-scale impacts caused by marine infectious disease include eelgrass (e.g. eelgrass wasting disease; reviewed by Burge et al. 2013), reef-building corals (multiple syndromes; reviewed by Sutherland et al. 2004; Harvell et al. 2007; Bourne et al 2009; Burge et al 2014), oysters (e.g. Dermo and MSX diseases, Ford & Trip 1996), abalone (e.g. withering syndrome; Friedman et al. 2000) and sea urchins (e.g. large scale of losses of *Diadema;* Lessios et al. 1984). Understanding the impacts of disease on biodiversity of large interconnected systems of highly mobile organisms (i.e. crustaceans, marine fishes and mammals) is more difficult. Additionally, diseases have had large impacts on both cultured and wild harvests of commercially important species, such as salmon [e.g. *Ichthyophonus* infection in marine and anadromous fish (reviewed in McVicar 2011; Burge et al. 2014) and viral infections in Atlantic and Pacific salmon (reviewed in Kurath & Winton 2011)], abalone (e.g. withering syndrome; Friedman et al. 2000), and crustaceans (e.g. protozoan infections of natural populations and viruses in aquacultured species; reviewed in Stentiford et al. 2012).

Managing disease is an important goal to maintain ecosystem function and biodiversity in the ocean and to limit the exposure to disease in both humans and marine organisms. Many of the land-based management techniques used in the terrestrial environment are not practical and/or successful in the ocean, including quarantine, culling and vaccination. The reduction of exposure to and impacts of marine disease may be achieved through reducing stressors such as coastal pollution, habitat loss, translocation of pathogens, and harvest practices. However, some stressors, such as those associated with climate change – that is changes to physical (e.g. changes in temperature, pH, and salinity) and biological (e.g. range shifts of organisms) characteristics of the ocean – will be difficult to reduce. Strategies to manage disease need to include long-term climate and organismal monitoring, experimental work to test effects of ocean change on host–pathogen interactions, and forecasting and decision-support tools to inform management. Factoring drivers of disease such as climate into management will be key to ensuring the long-term sustainability of diverse ocean ecosystems, and the benefits these ecosystems provide to people.

3. Challenges and approaches

3.1 Growing pressures and climate change

Increasing human populations, and their growing resource demands, are exacerbating the drivers of infectious disease emergence detailed above. Adding to these pressures are the impacts of climate change and associated shifts in species range, as well as the pathogens for which they may serve as a host or reservoir. For example, ecological niche models incorporating climate change scenarios for 2050 have suggested that the habitat range and distribution of the bat reservoir species for henipaviruses will expand, increasing human disease risk (Daszak et al. 2013). These risks may be compounded by increasing movement of species through trade and travel and the evolution of a more suitable habitat for invasive alien species.

Weight of the evidence and further research needs

- Research to date has shown strong evidence for the overlapping drivers of disease emergence and biodiversity loss. Anthropogenic activities are rapidly altering ecological and evolutionary systems under which hosts and pathogens operate, creating new dynamics and opportunities for disease transmission and spread.

- Further investigation is needed around the ecological factors (e.g. community composition, abundance, etc.) affecting disease risks for humans and other species in ecosystems. Disease ecology studies can provide insight on both host and pathogen dynamics. Understanding of disease in an ecosystem can be best served through One Health approaches that consider the links between humans, animals and the environment, thus providing a more integrated and broader understanding of disease risks as well as prevention and control strategies.

- Environmental impact assessments (EIAs) provide useful tools to guide risk prevention and mitigation. Incorporating health risks into EIA processes can provide a more robust evaluation of risks, including the high financial cost of potential disease emergence and outbreaks. Disease may also have significant impacts on ecosystems (e.g. to wild species and their provision of ecosystem services) in addition to human health.

3.2 One Health approach to drivers of infectious diseases

The integral infectious disease connections between domestic animals, humans and ecosystems are exemplified by the highly pathogenic avian influenza (HPAI) H5N1 panzootic. Evolving from a low-pathogenic strain, intensive poultry production, paired with inadequate biosecurity, enabled the emergence and spread of H5N1 among poultry flocks, geographies, and species, including infection of wild birds and humans (Karesh et al. 2012) Similarly, many neglected infectious diseases have an animal link. For example, echinococcosis, a zoonotic pathogen transmitted from a dog tapeworm, causes 200 000 human cases each year, costs an estimated US$ 2 billion in losses annually to the global livestock industry, and infects a range of wild species (Cardona et al. 2013; Karesh et al. 2012). These examples highlight the importance of disease surveillance across the species spectrum to enable early detection or early warning systems. While in some cases disease control measures may be harmful to biodiversity, they can also yield benefits for wildlife. Mass vaccination of cattle for rinderpest boosted wildebeest population numbers after large drops attributed to rinderpest infection. Surveillance in wildlife has subsequently been used to monitor rinderpest circulation (Couacy-Hymann et al. 2005). Surveillance and reporting employing a One Health approach may provide sentinel benefits to enable early detection of pathogens potentially transmissible between humans, wild species, and livestock. This is especially important given chronic under-reporting of disease in animals, including in food production, as well as changing ecological factors from climate change (de Balogh et al. 2013; Pinto et al. 2008).

In order to move from the currently reactive response to infectious disease emergence and spread, we must also go a step further to address the underlying drivers of disease emergence, many which also overlap with drivers of biodiversity loss (FAO 2013; Karesh et al. 2012; CBD 2012). This requires an integrated effort around ecosystems, human, and animal health, rather than a siloed one-species or one-discipline perspective. A One Health or ecohealth approach that considers the links between humans, animals (domestic and wild), and the environment can improve understanding of infectious disease drivers and dynamics and move from response to prevention measures (FAO 2013; Karesh et al. 2012). Given the high costs of disease emergence events (for example, the 2003 outbreak of SARS cost the global economy an estimated US$ 30 billion) and significant public health impacts (over one billion cases of infectious diseases annually), both the economic and health arguments for tackling root causes of disease emergence drivers may directly and indirectly serve to protect biodiversity (Karesh et al. 2012).

Moreover, given that health and land management decisions are rarely made on the basis of a single pathogen, we need to move towards a multiple pathogen approach and increase our focus on pathogens of major human health relevance. By closing these gaps we will improve our ability to identify synergies between biodiversity and net human infectious disease risk burden where they exist, and move to a predictive, impact-based framework. While EIAs may be commonly employed for potential environment-modifying projects, also applying health impact

Box 3: Sentinel surveillance opportunities for the prevention of Ebola outbreaks

The long-running and highly disruptive human Ebola outbreak in West Africa (responsible for >25 000 reported human cases between December 2013 and early April 2015) demonstrates the public health challenge posed by the Ebola virus. Despite global attention and response, over fifteen months into the outbreak the initial source of the outbreak had still not been definitively identified (WHO 2015). While the number of new cases had shown signs of decline as of early April 2015, intense transmission was continuing in parts of Guinea and Sierra Leone. Prior Ebola outbreaks in humans, and a concurrent outbreak in the Democratic Republic of Congo beginning in August 2014, have been linked to the hunting or handling of wild animals, with subsequent human–human transmission (Rouquet et al. 2005; Feldmann and Geisbert 2011). Some bat species are the suspected natural reservoir for the virus and are thought to harbour it without symptoms. Investigations of wild animal carcasses have detected infection and mortality in chimpanzees, gorillas and duikers, suggesting that they may serve as intermediate hosts for potential human spill-over (Rouquet et al. 2005). Ebola virus has also been recognized as causing severe declines in great ape populations, especially critically endangered wild lowland gorilla troops (Leroy et al. 2004; Olson et al. 2012).

Ebola virus outbreaks in humans are typically sporadic, presenting a challenge for ongoing detection and monitoring (Leroy et al. 2004). Data generated from the Animal Mortality Monitoring Network in Gabon and Republic of Congo and subsequently the United States Agency for International Development (USAID) Emerging Pandemic Threats 'PREDICT' programme suggest that surveillance for Ebola virus circulating in wildlife may enable early detection or prevention of Ebola virus outbreaks in humans (Rouquet et al. 2004; Olson et al. 2012). Finding fresh wild animal carcasses had been viewed as a food resource and a sign of good fortune for some hunting communities, but poses risks for human transmission (Karesh and Cook 2005). To manage and reduce risks from Ebola virus spill-over, reporting of deceased or sick animal sightings by hunters and foresters can provide important sentinel benefits for public health and conservation monitoring, informing opportunistic sampling by trained field teams who can respond to reported morbidities and mortalities in wildlife with sampling and testing efforts (Rouquet et al. 2005; Olson et al. 2012). Additionally, non-invasive great ape faecal sampling may provide a cost-effective surveillance method and provide data on Ebola virus exposures and survival to benefit conservation strategies (Reed et al. 2014). This One Health approach, paired with sharing of information on Ebola virus detection across health and wildlife authorities and local hunting communities, allows for targeted early detection efforts and implementation of preventive measures.

assessments – including wildlife disease risk analyses – can provide a more full understanding of potential disease risks to people, animals and the environment (Karesh et al. 2012).

3.3 Economic impacts

The high economic burden of disease – which has the potential to grow as anthropogenic activities increase risks of disease emergence and globalization enables rapid spread – may hinder development progress. Reactive disease control efforts have proven vastly expensive, as seen with SARS in 2003 (US$ 30–50 billion), Nipah virus in 1998 (over US$ 500 million) and many other recent disease outbreaks, and pandemics have been identified as having potentially catastrophic impacts that are global in scale (World Bank 2012). Over the past two decades, the cost of emerging diseases alone (in humans) has reached the hundreds of billions of dollars, and regionally endemic diseases have persistent financial implications, often to low- or middle-income populations (Karesh et al. 2012). While emerging diseases may have acute costs from short-term outbreaks, they also have the potential to become established in human populations and yield long-term costs. While pathogens causing disease in humans are primarily the focus of human infectious disease efforts, even non-zoonotic diseases in livestock can severely threaten health and livelihoods of smallholder farmers through loss of income and food security, and/or control costs.

Costs of disease may be borne by both the international community and local communities affected by disease-related disruptions. For example, based on UN estimates over US$ 600 million are needed to end the Ebola outbreak in West Africa, which began in December of 2013 but was not detected by health authorities until March of 2014 (Baize et al. 2014). In addition to the direct costs of response and control, the outbreak has the potential to yield extremely high indirect costs, with travel, trade, and other productivity also gravely affected and resources directed to fighting Ebola, potentially at the cost of treating other health threats. As the Ebola crisis highlights, public health infrastructure globally is largely reactive, with preventive efforts frequently hampered by limited knowledge about the source of disease (as also exemplified by the unknown animal–human transmission pathway for the Middle East Respiratory Syndrome (MERS-CoV) and the pathogens harboured in our environment that could be detrimental to humans. However, recent studies suggest that approximately three quarters of recently emerging diseases in humans have come from wildlife, with most of them caused by viruses, and thus provides a starting point for predicting and preventing future emergence efforts (Jones et al. 2008; Taylor et al. 2001). The cost of detecting 85% of viral diversity in mammals has been estimated at US$ 1.4 billion, or US$140 million per year over ten years (Anthony et al. 2013). While this represents a significant sum, it is only a small fraction of the cost of an emerging diseases event and its early detection may enable actions to prevent spill-over of some pathogens from animals to humans. Furthermore, routine disease surveillance of animals may provide sentinel benefits for humans for early detection of both infectious and non-infectious (e.g. heavy metals in ecosystems) health risks.

The efficiency gains of a One Health approach to zoonotic disease were recently highlighted in a report by the World Bank (2012) which also highlighted the limited investments in One Health at present. Specifically, it noted very low actual investments for wildlife health surveillance are being made, and estimated that between US$ 1.9 and 3.4 billion per year were needed (over ten years) to bring low- and middle-income countries up to WHO and OIE standards to support more integrated and prepared national human and animal health systems. Many low-income nations are also biodiversity-rich although public health infrastructure is poor, creating “hotspots” for disease emergence (see infectious disease chapter in this volume and Jones et al. 2008). As we move toward the SDGs, these should be considered necessary investments for the reduction of the health burden. In addition to human health benefits, biodiversity conservation efforts can also benefit from a more integrated disease surveillance approach. For example, rabies is a neglected disease concern for humans as well a mammalian domestic animals and wildlife, killing over 50 000 people annually worldwide, necessitating ongoing vaccination and/or population control methods in domestic animals, and causing major declines in some wild canid populations (e.g. African Wild Dog and Ethiopian Bale Wolf populations). Moreover, disease spill-over is not one-directional; wild and domestic animal populations may acquire disease directly from human contact. Integrated surveillance and control campaigns may be cost-effective means for the early identification of threats before they harm humans, domestic animals, or wild species (Machalaba and Karesh 2012).

3.4 Systems approach and collaboration

While most emerging diseases originate in wildlife, sustained infections are commonly transmitted among humans or through a domestic animal connection (Kock 2014). For example, HIV originated in non-human primates, but its principal ongoing transmission source for new infections is human–human. However, given the population impacts of HIV and other diseases that have emerged from wildlife, there are opportunities to move upstream toward more preventive efforts for future disease while still focusing on mitigating impacts of current ones. Vector-borne disease will always be a challenge for control from ongoing movement across boundaries (but it is the vector, and not wild host, which matters here) and attempts to eliminate vectors are frequently ineffective or lead to unintended and detrimental ecological consequences. Despite this, the main concern related to biodiversity and emerging disease remains the spill-over of microorganisms from wildlife into human-modified landscapes where the organisms occasionally evolve into pathogens (e.g. corona and influenza viruses). Importantly, the evolution of these pathogens is largely driven by the human system itself (landscape, domestic animals, artificial habitats, behaviour) and through peri-domestic wild species that have adapted to the modified landscape (Kock 2013; Jones et al. 2013). Infectious disease funding streams are currently heavily directed toward human–human prevention of new cases, but dedicating a small portion of funds to preventing future disease emergence could yield downstream cost savings.

To tackle the issues described above requires a highly collaborative and interdisciplinary, systems approach. But, the big question is, where to start? There is currently no reliable toolkit to accurately determine which of the candidate infectious agents will emerge as pathogens. Given limited resources and millions of potential species and billions of potential strains of micro-organisms, starting efforts might be targeted to detecting pathogen families that are known to be highly pathogenic to humans and other species and taking preventive measures, and refining risk analyses for wider pathogen pools as more knowledge is generated.

In light of this evidence, measures and policies to reduce risk of spill-over should include:

- On a precautionary principle, avoidance of high-density monoculture agriculture and human activity/settlement adjacent to highly biodiverse ecosystems (especially urban centres, mining, industrial and intensive livestock systems).

- Utilization of an ecological or "One Health" approach to disease, rather than a simplistic "one germ, one disease" approach to provide a richer understanding of human, animal and environment health links.

- High biosecurity of all industrial and intensive animal and plant agriculture, and more judicious or prudent use of antimicrobial agents in both human and animal medicine and food production systems to reduce selection pressure for evolution of resistant strains.

- More resilient diverse agriculture and sustainable harvesting systems. In the case of the latter some species are high risk for pathogens and should not be included in the human diet, e.g. non-human primates given their high genetic relatedness to humans (additionally, they constitute an unsustainable protein source). For example, the origin of the 2014 human Ebola outbreak in the Democratic Republic of Congo was linked to the butchering of an infected monkey. If non-human primates are hunted and consumed, these activities should be accompanied by intensive surveillance efforts for early detection and response to disease spill-over events.

- Advances in the identification and modelling of synthetic biological, ecological and anthropogenic parameters that drive the emergence of wildlife diseases, and analysis of risk mitigation strategies.

- Prevention of harvesting for wildlife trade and/or regulation for disease control in addition to source population sustainability.

- Increased systems research to better understand the mechanism of pathogen jumping and evolution and the effects of community composition, abundance, and other ecosystem dynamics.

- Careful management of tourism in biodiverse areas, in order to reduce risk of infection especially where anthropophilic vectors occur (there should also be measures in place to reduce the possibility of introduction of pathogens into these environments from people and domestic animals).

- Development and support for the inclusion of monitoring wildlife pathogens in national programmes of surveillance in health, agriculture and conservation.

- More proactive and integrated risk assessment and analysis, to be informed and refined by integrated infectious disease surveillance and response measures. Analysis, monitoring and management of infectious disease risks are warranted for both potential conversion of natural areas, as well as changing ecologies in urban areas (e.g. proposed "greening" of cities, which may change interactions between humans and other species). Some approaches that can be leveraged include:

    – Risk analysis tools, such as the approaches set forth in the OIE *Guidelines on assessing risk of non-native animals becoming invasive* and the OIE-IUCN *Guidelines to disease risk analysis*, can provide qualitative and quantitative measures of risk.

    – Surveillance and risk prediction systems can also support risk analysis. For example, in Brazil, the Information System of Wildlife of Oswaldo Cruz Foundation is designed to use mathematical models to build alerts of the occurrence of pathogens in wildlife with potential human involvement, with the participation of society and experts in mobile technology. Additionally, the USAID Emerging Pandemic Threats PREDICT programme has conducted pathogen surveillance in wildlife in 20 countries that are "hotspots" for disease emergence and worked closely with health, agriculture and environment ministries to characterize risks and interpret findings through a One Health approach (see case study in Part III of this volume).

These measures and policies are largely outside the competence levels of most human and animal health systems, which in any case are largely reactive. Policy and implementation should involve a One Health approach to ensure a politically, socially and economically acceptable solution to the whole of society, and not to the detriment of the environment.

ECOHEALTH ALLIANCE

MARIANA CERATTI / WORLD BANK PHOTO

8. Environmental microbial diversity and noncommunicable diseases

1. Introduction

Many countries worldwide, particularly in their urban centres, have undergone large increases in the incidences of chronic inflammatory disorders such as allergies, autoimmune diseases and inflammatory bowel diseases (Bach 2002), all of which are at least partly disorders of immunoregulation, where the immune system is attacking inappropriate targets (harmless allergens, self and gut contents respectively). Similar increases in these noncommunicable diseases (NCDs) are now occurring in emerging and urbanising economies.

There is also an increase in diseases associated with another consequence of disturbed immunoregulation: long-term background inflammation manifested as persistently raised C-reactive protein (CRP) in the absence of detectable medical cause. This is common in high-income countries, and is associated with cardiovascular disease, metabolic syndrome, insulin resistance, obesity (Goldberg 2009; Shoelson et al. 2007) and depression (Rook et al. 2014b; Valkanova et al. 2013). Finally, some cancers that are increasing in prevalence are also associated with poorly controlled inflammation (e.g. cancer of the colorectum, breast, prostate, classical Hodgkin's lymphoma and acute lymphatic leukaemia of childhood) (Rook and Dalgleish 2011; von Hertzen et al. 2011b).

The purpose of this section is to explore the relationship between these worrying disease trends, and defective immunoregulation attributable to diminishing microbial biodiversity.

2. The 'hygiene hypothesis': the updated concept

The expression 'hygiene hypothesis' emerged in 1989 and since then has had wide, often misleading, media appeal (Strachan 1989). The problem has been that although based on a crucial underlying insight (that microbial experience modulates our immune systems) it was initially interpreted narrowly in the context of allergic disorders, and there was a tendency to assume that the relevant microbes were the common infections of childhood (Dunder et al. 2007; Strachan 1989). However, the concept has broadened so that it is now a fundamental component of Darwinian (or evolutionary) medicine, with implications for essentially all aspects of human health (Rook et al. 2014b). The allergic disorders are only a part of the story, and neither hygiene nor the common childhood infections necessarily play an important role. For this reason, more recent terminology now employs terms such as the biodiversity hypothesis (von Hertzen et al. 2011a) or the Old Friends mechanism (Rook et al. 2014b) to refer to situations where changing patterns of microbial exposure, in concert with changing diets, are contributing to diminished immunoregulation, and to increased incidences of immunoregulatory disorders.

Earlier controversy surrounding this topic may be considerably reduced when the differing roles of major functional and evolutionary categories of organism are taken into account.

2.1 Categories of organisms

1) The 'Old' infections

Co-evolved with humans (Comas et al. 2013; Linz et al. 2007; Wolfe et al. 2007). Modulate the immune system so they can persist for life in small hunter-gatherer groups without killing the host, or being eliminated by the immune system. Progressively eliminated by modern medicine (*Helicobacter pylori,* blood and gut helminths etc.). Known to regulate the immune system and to act as 'Treg adjuvants': they encourage development of the regulatory T lymphocytes (Treg) that regulate the immune system (Babu et al. 2006; Correale and Farez 2013).

2) Symbiotic microbiotas

Co-evolved with humans. Loss of diversity in modern urban settings, due to caesarean delivery, lack of breast feeding, antibiotics (Rook et al. 2014b), and increasing uniformity of diet (Khoury et al. 2014; Thorburn et al. 2014). Known to drive development and regulation of the immune system (Round and Mazmanian 2010).

3) Supplements to the symbiotic microbiotas from the natural environment

Major differences exist between hunter-gatherer, traditional rural and urban gut microbiotas (De Filippo et al. 2010; Yatsunenko et al. 2012). In an experimental model, exposure to the outdoor environment increased firmicutes, particularly lactobacilli (which produce short-chain fatty acids that have anti-inflammatory effects), whereas rearing in the indoor environment led to increased expression of inflammatory molecules in the gut epithelium (Lewis et al. 2012; Mulder et al. 2009). Some soil spore-formers germinate and replicate in the human gut (Hong et al. 2009). Horizonal gene transfer from environmental microbiota to symbiotic microbiota has been documented, although transfer between microbiota where donor and recipient both inhabit the gut is more common (Smillie et al. 2011).

4) The 'crowd' infections; particularly common virus infections of childhood

Recently acquired (after Neolithic revolution) because they either kill or immunize, and so could not evolve or persist in small hunter-gatherer groups because a large enough population is required for susceptible individuals to persist (Wolfe et al. 2007). Therefore humans did not co-evolve with them as down-regulators of the immune system, and epidemiological studies have confirmed that the crowd infections do not protect children from allergic disorders (Benn et al. 2004; Bremner et al. 2008; Dunder et al. 2007) and in fact often trigger them (Yoo et al. 2007).

Therefore, using this simple functional classification it is possible to make a number of well-documented statements.

i) The Old infections and the commensal microbiotas (as well as their supplements, as yet poorly defined, from animals and the environment) have potent immunoregulatory effects with well-studied and documented molecular pathways, summarized in the next section (reviewed in Rook et al. 2014b).

ii) The Old infections are rapidly and progressively eliminated by modern medicine and lifestyles.

iii) The biodiversity of the microbiotas is restricted by the modern lifestyle.

iv) Exposure to the Crowd infections should be avoided rather than promoted.

Therefore, depletion of categories 1), 2) and 3) is relevant to changes in regulation of the human immune system, whereas depletion of category 4) has *not occurred* in urban populations (except where an efficient vaccine has been deployed) and is in any case not associated with changes in immunoregulatory circuits. Indeed, these infections often act as triggers of allergy or autoimmunity (Yoo et al. 2007). The original formulation of the hygiene hypothesis focused attention on the crowd infections, but this was an error, and the protection against allergic disorders attributed to the presence of older siblings (Strachan 1989), and assumed by many at that time to be a protective effect of the childhood virus infections, is now attributed to enhanced transmission of microbiota (Penders et al. 2013).

2.2 Lifestyle factors that reduce exposure to microbial biodiversity

While modern medicine tends to eliminate the Old infections, lifestyle factors in high-income urban settings reduce exposure both to maternal microbiota and to organisms from the natural environment (categories 2 and 3 above). Delivery by caesarean section, lack of breast feeding and excessive use of antibiotics in early childhood all delay, reduce or modify accumulation of essential microbiota (reviewed referenced in Rook et al. 2014a). The protective effect of cleaning a child's dummy/pacifier by sucking it, and immediately replacing it in the baby's mouth is an elegant illustration of the need for trans-generational transmission of microbiota (Hesselmar et al. 2013).

2.3 Links to socioeconomic status (SES)

The factors mentioned in the previous paragraph might be exacerbated in families of low SES, who tend to eat unvaried fast-food diets and more highly processed foods that lack any trace of soil and its microbes, whose homes are less likely to include gardens, and who lack access to travel, overseas holidays and rural second homes (Rook et al. 2013).

2.4 Immunoregulatory pathways driven by organisms of categories 1, 2 and 3

The immune system is potentially dangerous if it attacks inappropriate targets such as harmless allergens in air or food, the host's own tissues, or essential gut microbiota. When these three types of inappropriate immune response occur they result in allergy, autoimmune disease or inflammatory bowel disease respectively. The immune system has a number of complex mechanisms, known collectively as immunoregulation, to *suppress unwanted responses*. While a full exploration of this topic falls outside the scope of this chapter, it is important to note that the immunoregulatory effects of categories 1, 2 and 3 are well documented. Old infections (such as helminths) have been shown to drive immunoregulation in humans (Babu et al. 2006; Correale and Farez 2013), and to block or treat animal models of numerous chronic inflammatory conditions (reviewed in Osada and Kanazawa 2010). Molecular structures responsible for immunoregulation are being identified (Grainger et al. 2010; Harnett et al. 2010; Kron et al. 2012). Regulatory T cells (Treg), provide one important immunoregulatory mechanism. When Argentinian multiple sclerosis (MS) patients become infected with helminths, the disease stops progressing and circulating myelin-recognising regulatory T cells (Treg) appear in the peripheral blood (Correale and Farez 2007), indicating that the helminths act as Treg adjuvants. Thus some helminths can be shown to specifically expand Treg populations (Grainger et al. 2010), or to cause dendritic cells (DC) to switch to regulatory phenotypes that preferentially drive immunoregulation (Hang et al. 2010; Smits et al. 2005).

Gut bacteria are also able to do this. A polysaccharide from *Bacteroides fragilis,* commonly present in the human gut, can expand Treg populations (Round and Mazmanian 2010), as can some members of clusters IV and XIVa of the genus Clostridium (Atarashi et al. 2011), some lactobacilli (Poutahidis et al. 2013), and very probably unidentified organisms from the natural environment, discussed later (Lewis et al. 2012). Some of these effects are mediated via short chain fatty acids (SCFA) that act on G-protein-coupled receptors (GPCR) (Thorburn et al. 2014). SCFA are generated by microbiota that ferment dietary fibre.

It seems unlikely that we will want to bring back all the Old infections, unless we create a 'domesticated', perhaps genetically modified helminth that could be administered to all children (Parker and Ollerton 2013). On the other hand we should be able to compensate for loss of the Old infections by optimizing exposure to categories 2) and 3) the microbiotas and their supplements from the natural environment. From a medical point of view the question is whether we can compensate for loss of the Old infections and depletion of our microbiotas by restoring those microbiotas and restoring inputs from a carefully maintained and biodiverse natural environment.

3. Commensal microbiotas and environmental biodiversity

From a biological perspective, humans are not individuals. We are ecosystems. Up to 90% of our cells are microbial, and the various microbiotas, particularly the gut microbiota, contain at least 100 times more genes than does our human genome (Wikoff et al. 2009). Consequently, approximately 30% of our metabolome (small molecules circulating in the blood) are products of enzymatic processes encoded in microbial DNA rather than in the human genome (Wikoff et al. 2009). We now know that the microbiotas play a role in virtually all aspects of our physiology, in addition to priming the immune system and its immunoregulatory pathways as described in the previous section. While there is no such thing as a germ-free human, work in experimental animals has revealed that the microbiota influence development of the brain, hypothalamo-pituitary-adrenal axis (HPA), gut, bones etc. (Gilbert et al. 2012; McFall-Ngai et al. 2013). The microbiota also influences energy retrieval from food sources and the likelihood of obesity, cardiovascular disease, metabolic syndrome and type 2 diabetes (Tremaroli and Backhed 2012). In animals, the microbiota modulate brain development and responses to psychosocial stressors (Bailey et al. 2011; Heijtz et al. 2011), and human experiments have shown that the gut microbiota influences aspects of cognition involved in human emotion and sensation (Tillisch et al. 2013). This finding may have significant implications for better understanding mental health, and attempts to treat psychiatric states by modulating the microbiota are beginning to be published (Messaoudi et al. 2011).

Therefore, in the context of this chapter, crucial questions are: 1) *are the human microbiotas losing biodiversity?* And, if so: 2) To what extent is reduced biodiversity of human microbiotas a consequence of changes in the biodiversity of the environment in which we live? 3) What are the implications for human health?

4. Loss of biodiversity: consequences for human health

Reduced gut microbial biodiversity is often found to associate with poor control of inflammation. Mice with lower microbial diversity have more biomarkers of inflammation (Hildebrand et al. 2013). Gut microbiota of limited diversity is also characteristic of human inflammation-associated conditions such as obesity and inflammatory bowel disease (Rehman et al. 2010; Turnbaugh et al. 2009). Similarly, diminished microbiota biodiversity in institutionalized elderly people correlates with diminished health and raised levels of peripheral inflammatory markers such as interleukin 6 (IL-6) (Claesson et al. 2012).

The same is probably true for skin disorders (Zeeuwen et al. 2013). There is an abnormal microbiota and reduced diversity on skin subject to eczema, with a tendency to return to greater diversity following effective treatment (Kong et al. 2012), and similar findings in psoriasis (Fahlen et al. 2012). It has been suggested that throughout human evolution the skin microbiota have included ammonia-oxidising bacteria (AOB) that would help to explain the presence of large quantities of ammonia and nitrate in human sweat (Whitlock and Feelisch 2009). The AOB convert this to rapidly absorbed nitrite and nitric oxide (NO) that regulates blood pressure and the immune system. AOB are very sensitive to triclosan and alkylbenzene sulfonate detergents, so they are absent from human skin in modern high-income settings.

Further information and references on some of the conditions listed in this paragraph are described below.

4.1 To what extent is reduced biodiversity of human microbiota a consequence of changes in the biodiversity of the environment in which we live?

Humans and other mammals obtain much of their microbiota from their mothers during delivery, and via breast milk (which is not sterile) and from family members. However many, probably *all animal species* (including humans), obtain components of their microbiota from soil (Mulder et al. 2011; Troyer 1984). It is an interesting possibility that geophagy (the eating of earth) by babies and infants is an evolved strategy for the uptake of soil organisms. This is manifested as the 'oral' phase, when all babies put whatever they can reach into their mouths. The quantities of soil and faecal matter that can be ingested by human babies with access to these materials (for example in an African village) are astonishing (Ngure et al. 2013). Circumstantial evidence that humans acquire important microbial biodiversity from the environment comes from studies of the effects of contact with farms, animals, and green spaces discussed below.

4.1.1 Health benefits of exposure to farms and farmland

Exposure of the pregnant mother or infant to the farming environment protects the child against allergic disorders and juvenile forms of inflammatory bowel disease (Radon et al. 2007; Riedler et al. 2001; Timm et al. 2014). This protection appears to be at least partly attributable to airborne microbial biodiversity assayed in children's bedrooms (Ege et al. 2011). Similarly mere proximity to agricultural land rather than to urban agglomerations increased the biodiversity of skin microbiota, reduced atopic sensitization and increased release by blood cells of IL-10, an anti-inflammatory mediator (Hanski et al. 2012).

4.1.2 Farm animals and dogs

Some of the relevant microbiota come from animals. Contact with cows and pigs protects against allergic disorders (Riedler et al. 2001; Sozanska et al. 2013). Contact with dogs, with which humans have co-evolved for many millennia (Axelsson et al. 2013; Thalmann et al. 2013), also protects from allergic disorders (Aichbhaumik et al. 2008; Ownby et al. 2002), and people share their microbiota via dogs (Song et al. 2013), which also greatly increase the microbial biodiversity of the home (Dunn et al. 2013; Fujimura et al. 2010). Exposure to high levels of bacterial and fungal

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components in house dust was associated with diminished risk of atopy (the tendency to develop allergic sensitisation to environmental allergens) and wheeze, though the origins of the organisms was not ascertained (Karvonen et al. 2014; Lynch et al. 2014). In a developing country, the presence of animal faeces in the home correlated with better ability to control background inflammation (CRP levels) in adulthood (McDade et al. 2012b), and in Russian Karelia (where the prevalence of childhood atopy is 4 times lower, and type 1 diabetes is 6 times lower than in Finnish Karelia), house dust contained a 7-fold higher number of clones of animal-associated species than was present in Finnish Karelian house dust (Pakarinen et al. 2008).

4.1.3 Green space

Living close to green spaces reduces overall mortality, cardiovascular disease, and depressive symptoms, and increases subjective feelings of well-being (Aspinall et al. 2013; Dadvand et al. 2012; Maas et al. 2006; Mitchell and Popham 2008). This health benefit has been attributed to multiple factors including exercise, exposure to sunlight and psychological effects. A detailed review and critique of these explanations has been published elsewhere (Rook 2013). Recent work suggests that the health benefits are not attributable to exercise alone (Lachowycz and Jones 2014; Maas et al. 2008), and in light of the clear-cut observations on exposure to farms and animals, exposure to diverse environmental microbiota is becoming the most likely explanation. For example, the gut microbiota of United States citizens is different from that of Amerindian hunter-gatherers and Malawian rural farmers, and strikingly less biodiverse (Yatsunenko et al. 2012). Particularly relevant experiments have been performed with piglets, showing that when maintained with the sow in a field they developed a characteristic gut microbiota rich in Firmicutes, particularly Lactobacilli. On the other hand similar piglets maintained with the sow on the same diet, but in a clean indoor environment developed a gut microbiota that was deficient in Firmicutes, and biopsies of the gut epithelium revealed increased expression of inflammatory genes such as Type 1 interferon and major histocompatibility complex class I (Mulder et al. 2009). Moreover, the piglets deprived of environmental exposure had reduced numbers of regulatory T cells and a predisposition to making antibody following introduction of a novel food (Lewis et al. 2012). This represents an elegant model of the way that human babies are reared in high-income settings with minimal contact with environmental biodiversity, and parallels the rising incidence of food allergies and other immunoregulatory abnormalities in such babies.

Thus **the natural environment supplements and modulates the microbiota in a way that is relevant to regulation of the immune system.** This area is currently under-investigated, particularly the role of spore-forming bacteria that are usually considered to be soil organisms, but which can germinate and replicate in the human gut (Hong et al. 2009; discussed and referenced in Rook et al. 2014b). It is important to note that we do not currently know how much of the human microbiota is derived from the microbial environment, though work on this point is in progress, and the overlaps between gut and root microbiotas have been discussed (Ramirez-Puebla et al. 2013). However it has been demonstrated that germ-free mice can develop a functioning gut microbiota following exposure to microbial communities from soil, and from other environmental sources, though these organisms get displaced by more mouse-adapted strains when co-housed with mice carrying normal mouse microbiota (Seedorf et al. 2014). A recent study, using novel computational strategies was able to assemble the complete genome of 238 intestinal bacteria, 76% of which were previously unknown (Nielsen et al. 2014). Similar methods have not, to our knowledge at the time of publication, been applied to the microbiota of the natural environment.

4.1.4 Fermented foods and beverages

Fermentation of vegetables (Breidt et al. 2013; Swain et al. 2014), meat (Leroy et al. 2013) and beverages (McGovern et al. 2004) was another source of human intake of microbiota from the environment. Chemical analyses of residues in pottery reveal that some of these methods were in use at least 9000 years ago (McGovern et al. 2004) and probably a great deal earlier (McGovern 2009). A mutation in alcohol dehydrogenase 4 that increased the efficiency of alcohol metabolism appears to have arisen in distant ancestors of mankind about 10 million years ago, perhaps triggered by consumption of fruit that had fermented after falling to the ground (Carrigan et al. 2014). Lactic fermentation of vegetables (e.g. sauerkraut, kimchi, gundruk, khalpi, sinki etc) or of meat (for example the Eskimo fermented fish, walrus, sea lion and whale flippers, beaver tails, animal oils and birds) adds nutritional and microbiological diversity to the diet (Leroy et al. 2013; Selhub et al. 2014; Swain et al. 2014). Fermentation increases the content of vitamins, lactoferrin, bioactive peptides and phytochemicals such as flavonoids which may in turn modulate our own intestinal microbiota (Lu et al. 2013). The increasing interest in modern fermented foods, and in sourcing new probiotics from fermentation processes and from the environment is exploiting the fact that human metabolism has evolved in the presence of such organisms and might have developed a need for their presence.

4.1.5 Horizontal gene transfer

In addition to exchange of whole organisms with animals and the natural environment, we need to consider horizontal gene transfer (HGT) (Smillie et al. 2011). This is common between bacteria and recent work has revealed the existence of a global network of HGT between members of the human microbiota, even between phylogenetically very divergent bacteria separated by billions of years of evolution. Exchange was related to similarity of ecology rather than phylogeny. Examples include the horizontal transfer of genes encoding the antibiotic resistome from soil microbes (Forsberg et al. 2012). This is worrying because huge increases in antibiotic resistance genes are being detected in the microbiota of farm waste as a result of antibiotic use in animal husbandry (Zhu et al. 2013). However HGT also plays essential beneficial roles. Consumption of seaweed by Japanese people induces horizontal transfer to their microbiota from environmental microbes of genes that enable the catabolism of novel seaweed-associated carbohydrates (Hehemann et al. 2012). Thus the adaptability of the human microbiota depends upon appropriate contact with potential sources of genetic innovation and diversity, and might therefore be threatened by loss of biodiversity in the gene reservoir of environmental microbes.

4.2 Life history plasticity, and microbiota as epigenetic inheritance

Evolutionary biologists consider that life-history variables (such as litter size, birth weight, age at sexual maturity, adult weight and height) can be crucial developmental adaptations to a changing environment. However these life history variables can change stepwise over several generations even when the driving environmental change remains constant after it has first occurred (Price et al. 1999; Wells and Stock 2011). For example, improved nutrition in a colony of macaques led to progressive increases in female adult weight (and to increases in the birth weights of offspring) over 5 generations (Price et al. 1999). How is this mediated? Clearly a given genotype would be expected to yield a fixed phenotype under fixed conditions. Therefore epigenetic and developmental mechanisms are usually invoked to explain these generational effects. Such explanations are made more convincing when the **microbiota are considered as part of the epigenetic inheritance of the infant**. (Interestingly some products of the microbiota exert anti-inflammatory effects by inhibiting histone deacetylases (HDACs), so the microbiota is directly involved in epigenetic immunoregulation (Thorburn et al. 2014)). Dietary effects will alter the microbiota, which when passed on to the next generation will programme the immune system so that it is different from that of the mother, and that immune system will then interact with further environmentally-driven changes to the microbiota.

4.2.1 Detrimental microbiota in unhealthy buildings

The previous paragraphs emphasise that humans evolved in a natural environment and in contact with animals. Until recently even our homes were constructed with timber, mud, animal hair, animal dung, thatch and other natural products, and ventilated by outside air. By contrast, modern buildings are constructed with synthetic materials, plastics and concrete, while the timber and cardboard are treated with adhesives and biocides, and ventilated by air conditioning systems. When these modern structures degrade, or become damp, or accumulate condensation in cavity walls, they do not become colonized with the bacterial strains with which we co-evolved. They harbour a low biodiversity, and become habitats for unusual strains that we did not encounter during our evolutionary history, some of which synthesise toxic molecules that we are unable to inactivate (Andersson et al. 1998; Sahlberg et al. 2010). Some examples of "sick building syndrome" have been tentatively attributed to prolonged exposure to these inappropriate airborne microbiota (Andersson et al. 1998; Sahlberg et al. 2010).

5. Commensal microbiota and noncommunicable diseases

As outlined above, as societies become westernized and urbanized, there are striking increases in chronic inflammatory disorders (autoimmunity, allergies and inflammatory bowel diseases (IBD)) that are at least partly attributable to defective immunoregulation, in which the gut microbiota plays a major role (reviewed in Rook et al. 2014b). Most of the epidemiological evidence applies to these three groups of conditions, covered in the previous paragraphs.

However other major health problems rise in parallel with the classic trio of chronic inflammatory disorders already mentioned (autoimmunity, allergies and IBD), and in these conditions also there are reasons for implicating the microbiota, the environment and immunoregulation.

5.1.1 Obesity, metabolic syndrome and type 2 diabetes.

The gut microbiota of lean and obese human individuals differ, and can transfer the tendency to leanness or adiposity to germ-free mice maintained on a standard diet (Turnbaugh et al. 2006). The mechanisms by which microbiota influence adiposity have been reviewed (Karlsson et al. 2013). They include effects on efficiency of energy harvest from ingested food, and complex effects on the function of the body fat-regulatory circuits that involve the central nervous system, leptin, neuropeptide Y, proglucagon and brain-derived neurotrophic factor (Schele et al. 2013a; Schele et al. 2013b). Some of these neuroendocrine phenomena may be secondary to central nervous system effects of inflammatory mediators such as IL-1 and IL-6 (Schele et al. 2013a), and indeed chronic inflammation contributes to insulin resistance and obesity via several pathways (Shoelson et al. 2007). Anti-inflammatory Foxp3+ regulatory T cells (Treg) in abdominal fat control the inflammatory state of adipose tissue, and the abundance of Treg in abdominal fat is inversely related to insulin resistance (Feuerer et al. 2009). A diet of western fast food aggravates the immunoregulatory deficit, promotes a *low* ratio of Treg to Th17 cells (pro-inflammatory), and drives abdominal adiposity in humans and mice (Poutahidis et al. 2013). This diet was shown epidemiologically to lead to obesity (Mozaffarian et al. 2011). Fatty diets and the accompanying dysbiosis can also increase gut leakiness and so increase uptake of pro-inflammatory products such as endotoxin (Cani et al. 2008).

The adipogenic and pro-inflammatory effects of the western fast food diet can be opposed by a probiotic (*Lactobacillus reuteri*) via a pathway that depends on the simultaneous presence of a *normal gut microbiota*, and is mediated by Treg (Poutahidis et al. 2013). (Interestingly, some strains of *L. reuteri* used in human food production might be derived from mouse gut microbiota (Su et al. 2012)). Thus the nature and diversity of the gut microbiota, together with the poorly documented inputs of microorganisms from the natural environment, may have multiple metabolic, neuroendocrine and immune-mediated effects on obesity, metabolic syndrome and insulin resistance, which are all major problems of our time.

5.1.2 Cancers associated with poorly regulated inflammation

The incidence of a number of cancers also increases in high-income urbanized settings in parallel with the chronic inflammatory disorders. These include cancer of the colorectum, breast and prostate, classical Hodgkin's lymphoma and acute lymphatic leukaemia of childhood (Rook and Dalgleish 2011; von Hertzen et al. 2011b). Inflammation can enhance mutation (Colotta et al. 2009) and so play a role in carcinogenesis, but 'smouldering' inflammation that is not obviously related to any external inflammatory stimulus is common in tumours (Porta et al. 2009) and releases growth factors and angiogenic factors that enhance growth, vascularization and metastasis (Balkwill 2009; O'Byrne et al. 2000; Porta et al. 2009). Interestingly non-steroidal anti-inflammatory agents, such as cycloxygenase-2 (COX-2) inhibitors, reduce the risk of developing colon and breast cancer and reduce the mortality caused by them (Cuzick et al. 2009).

The epidemiology of the cancers that increase in high-income settings is strikingly similar to that of the chronic inflammatory disorders. For instance, age-specific incidence rates for specific cancers in Asians correlate with the state of economic development of their country of residence. Incidences are much lower in Asians living in India compared to those living in the United Kingdom or United States (Rastogi et al. 2008). Another example is acute lymphatic leukaemia, which shows striking parallels with the epidemiological findings that gave rise to the original version of the hygiene hypothesis (Greaves 2006; Strachan 1989). A study in northern California provided preliminary evidence that protection from acute lymphatic leukaemia is proportional to the number and frequency of social contacts (Ma et al. 2002). A large population-based case-control study (The UK Childhood Cancer Study (UKCCS)) revealed further evidence that social contacts in infancy can reduce the risk of childhood acute lymphatic leukaemia (Gilham et al. 2005).

Animal models have cast much light on the links between environmental organisms, immunoregulation, inflammation and cancer (Erdman et al. 2010). Inflammatory signals from bacteria in the gut can trigger mammary, colorectal and prostate cancers in mice (Erdman et al. 2010; Lakritz et al. 2014). Tumourigenesis can be attenuated by immunoregulatory pathways triggered by appropriate Treg-inducing organisms (Erdman et al. 2010). For example, in two different mouse models (one genetic, and one dietary) mammary carcinogenesis was inhibited by exposure to *Lactobacillus reuteri*. The mechanism was found to be the induction of CD25+Foxp3+ Treg (Lakritz et al. 2014).

Thus, although excessive immunoregulation might be permissive for some cancers by decreasing anti-tumour immunity, there is strong evidence that faulty immunoregulation leading to chronic background inflammation can provoke mutation and tumourigenesis, and contribute growth factors that favour tumour development, vascularization and spread. Since the microbiota plays a major role in immunoregulation and is supplemented by organisms from the natural environment, it is reasonable to postulate that changes to the pool of environmental microorganisms have consequences for the risk of such tumours.

5.2 Depression, reduced stress resilience and poorly regulated inflammation

It is estimated that depression will become the second major cause of human disability by 2030 (Mathers and Loncar 2006). Chronically raised levels of inflammatory mediators are routinely associated with risk of depression in high-income countries (Dowlati et al. 2010; Gimeno et al. 2009; Howren et al. 2009; Rook et al. 2014b; Valkanova et al. 2013), and the mechanisms have been reviewed elsewhere (Miller et al. 2013). It should be noted that clinical administration of interferon alpha (IFN-a) commonly causes depression as a side-effect (Raison et al. 2009). Interestingly, one study failed to find a correlation between depression and raised CRP in a low-/middle-income country (McDade et al. 2012a).

In low-income settings, exposure to microbial biodiversity is greater and inflammation is shut off when episodes of infection are terminated, so that chronic elevated biomarkers of inflammation are not seen (McDade 2012). Thus decreasing exposure to microbial biodiversity, by reducing the efficiency of immunoregulatory circuits, is likely to be contributing to the increases in depression, and reduced stress resilience in high income settings (Rook et al. 2013).

6. Ways forward: preliminary recommendations for global and sectoral policy

What are the practical implications of these links between microbial exposures, microbial biodiversity, regulation of the immune system, and chronic inflammatory disorders?

6.1 Better understanding the links between microbial diversity and health

Practical recommendations are hampered by lack of precise information. Important areas for further research include:

a.1) *What are optimal compositions of the microbiota?* The physiological, metabolic and immunoregulatory roles of the microbiota are not in doubt, and constitute one of the most rapidly expanding and exciting branches of medical research. Nevertheless the techniques used, despite rapid progress, remain imprecise at the species level, and in most cases it is not yet possible to reliably link particular microbial species with health or illness. Even if we did have this knowledge, we do not yet know how to reliably bias the composition of the microbiota in the desired direction. **We also do not know whether humans with different genetics and**

Box 1: *Clostridium difficile;* a practical example of modulating gut microbiota

A gastrointestinal disorder characterized by diarrhoea and pain, caused by overgrowth of *Clostridium difficile* in the colon, provides a remarkable clinical example of the crucial importance of a correct balance of organisms within the gut microbiota, and illustrates practical ways of correcting such imbalance. Many people carry small numbers of *C. difficile* in their guts, but in some individuals antibiotic use can lead to overgrowth of this species, and to potentially life-threatening colitis aggravated by toxin production. (The same phenomenon is commonly seen in antibiotic-treated pet guinea-pigs (Rothman 1981)). Recently it has been observed that faecal microbiota transplantation (FMT) is an effective treatment in about 90% of patients (Cammarota et al. 2014). FMT involves administering faecal organisms from a normal donor (often a healthy family member). FMT suppresses growth of *C. difficile* and permits re-establishment of a normal microbiota. FMT is also undergoing trials in IBD, irritable bowel syndrome, and other chronic inflammatory conditions, though results remain variable (Borody et al. 2013).

Three important points need to be made here. First, as we learn more about the composition of a healthy microbiota and develop better ways of driving appropriate stable modifications of the microbiota, so our ability to treat diverse immunoregulatory and inflammatory disorders is likely to increase: this might also involve use of organisms from the natural environment. Secondly, we do not yet know whether people with different genetic backgrounds, or eating different diets, will require a different microbiota, though this is likely. Thirdly, as the number of conditions known to be modulated by the microbiota increases, so the selection of donors becomes more difficult. For example the material outlined in previous sections implies in addition to screening the donors for infections and load of *C. difficile*, we need to be sure that the donor is not obese, or at risk for cancer, cardiovascular disease, autoimmune disease, IBD, allergies or depression.

different diets require different microbiotas, although recent evidence suggests that this is likely.

a.2) *The nature of beneficial organisms from the natural environment*. The mother, family members and other people are major sources of microbiota, but the epidemiological data presented above provide powerful evidence to suggest that these microbiota are supplemented by organisms (and genes via horizontal gene transfer) from the natural environment and from animals. However, these organisms have not been formally identified. Experimental work with piglets strongly supports the view that the natural environment provides organisms that drive immunoregulation and suppress immune responses to novel foods, but again, the organisms involved have not been formally identified. This is a priority area for research.

6.2 Mainstreaming across health- and biodiversity-related sectors

It is difficult to make clear recommendations until the questions addressed in the previous sub-section are better defined. As such knowledge increases we will be able to offer more precise guidance on some of the relevant issues listed below.

b.1) **Agricultural methods**: Extensive monoculture and chemical use will reduce environmental biodiversity, and so reduce the adaptability of the human microbiota, which depends upon supplementation with organisms from the environment, and contact with potential sources of genetic innovation and diversity. However the evidence that organic farming increases biodiversity at the floral, faunal (Schneider et al. 2014) and microbial level is suggestive but incomplete and inconsistent (Sugiyama et al. 2010). The use of antibiotics in animal husbandry results in large increases in the abundance of antibiotic resistance genes (Zhu et al. 2013). Not only is this inherently undesirable, but is also likely to cause changes in the composition of the microbiota.

b.2) **Human behaviour; targeted hygiene**: The public should be taught the concept of 'targeted' hygiene. The sound bites generated by the 'hygiene hypothesis' has led to erroneous media backing for the notion that "we are too clean for our own good", despite the massive health benefits of hygiene. The public needs to understand, for example, the difference between the dangers of the gut microbiota of an uncooked chicken, and the benefits of contact with maternal microbiota, green spaces, animals and the natural environment.

b.3) **Antibiotics**: There is strong evidence that antibiotic use in childhood increases the risk of a wide range of chronic inflammatory and metabolic disorders in childhood and later life.

b.4) **Health benefits of fermented foods/ traditional diets:** Fermentation of vegetables, meat, oils and beverages can be traced back many millennia, as discussed in section 4.1.4. The fermentation process adds nutrients and microbiological diversity (Selhub et al. 2014). It is likely that humans have evolved a requirement for the fermenting organisms and their products, and it is widely believed that these foods provide health benefits. Although the science is strongly suggestive and most workers in the field are confident that fermented foods, probiotics and prebiotics will one day play a role in treatment and prevention of NCDs and inflammation-dependent psychiatric diseases, clinical trial data with the existing preparations have been inconsistent as revealed in recent rigorous reviews (Frei et al. 2015; West et al. 2015). More effort should be made to 'mine' traditional fermentation processes for novel probiotics before the diversity of strains is lost (Swain et al. 2014), and clinical trials should be more specifically targeted.

b.5) **Food supplements**: Food companies potentially have a major role to play in this endeavour. Too much testing of probiotics (and prebiotics) has been conducted with unsuitable organisms (and oligosaccharides) simply because the company concerned has the relevant intellectual property rights, or access to a bulk manufacturer of the strain in question. Probiotics

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have multiple modes of action. For example, when immunoregulation is required, it is obviously essential to test a probiotic that has *that* particular property (Frei et al. 2015), rather than a strain that acts by blocking an ecological niche in the gut and reducing pathogen access, however useful this property might be in other contexts. Some probiotics based on the spores of environmental *Bacillus* species are also marketed for human and animal use, but we are not aware of any systematic attempt to identify other relevant environmental organisms (as pointed out in a.2 above), though such work is in progress.

b.6) **Design of cities**: The realization that much of the health benefit of green spaces is not attributable to exercise alone and is likely to be due to exposure to microbial biodiversity leads to the possibility that not all green spaces need to be large parks appropriate for team sports. Multiple, small, high quality green spaces, designed to harbour the optimal fauna, flora and accompanying microbiota, might provide a major health benefit. These could include roof gardens, vegetated walls, grass verges etc. In London, environmental engineers have created "edible bus stops", which are small community gardens often located at bus stops where people congregate (http://www.theediblebusstop.org/). These projects are mostly driven by aesthetic considerations, whereas we now have medical reasons for supporting and amplifying such movements. This concept will again be facilitated when we have clear answers to question a.2) outlined above; what is the optimal flora to plant? How do we encourage the organisms that we want? It is worrying that use of water supplies contaminated with antibiotics on city parkland is changing the pattern of antibiotic resistance genes in the local soil, and so inevitably distorting the natural microbiota of these urban green spaces (Wang et al. 2014).

b.7) **Interdisciplinary publications and media attention**: The health world concentrates its reading, research and publications in medically-orientated journals while ecologists, environmental engineers, soil scientists and city planners disseminate their information in quite different ways. We need to encourage cross-disciplinary media attention and review publications.

6.3 Giving policy-makers an idea of tools available

An important consideration for policy-makers is that our knowledge of the microbiome is changing extremely rapidly, but the tools to perform these analyses and their limitations are also changing very rapidly. It is therefore a substantial risk that technologies or findings will be adopted before they are robust, leading to unstable conclusions, but at the same time a risk that powerful technologies of findings that could have large impact on people's lives will not be deployed in a timely fashion. This section describes some of these considerations.

6.3.1 Assessment

There is need for interdisciplinary studies, where epidemiologists work closely with microbiologists studying the microbiota of the environment (plants and soil), transport systems, homes, offices and public buildings. We already know that microbial biodiversity in a child's bedroom correlates with reduced risk of asthma and atopy (Ege et al. 2011). It will be important to extend such studies to other situations. For example, how does the microbial biodiversity of an underground train line (subway) that never runs above ground, compare with that of a line that is sometimes above ground (e.g. respectively, the Victoria and Piccadilly lines in London)? Are there detectable differences in the proportion of organisms from the natural environment? Are there detectable influences on the health of the passengers? Unfortunately transport companies and organisations are extremely unwilling to allow such investigations. Can we make the technology cheap enough and develop a robust enough database that individual families are willing and able to perform microbial tests of their homes, as they may already be doing when concerned about fungi? Can relevant governmental entities play an important role by facilitating rather than obstructing the study of public buildings and the effects of features of their microbiology on the health of their inhabitants or visitors?

Methods available

Skin microbiota can be sampled by lightly pressing a sterile swab on the skin. Faecal samples are also easy to collect. Questionnaires suitable for assessing health, disease prevalence and mental state are well validated. The progress in developing DNA sequencing and bioinformatic techniques has been rapid, and the microbial composition of any sample can be determined. Thus it is possible to couple disease epidemiology with biodiversity measurements. Similarly high-sensitivity C-reactive protein (CRP) assays are easy to perform and give a good measure of background inflammation levels. At present, most studies have focused on bacteria, although the viruses, fungi and microbial eukaryotes in general are also important components of the microbiota and are becoming increasingly feasible to assay. Similarly, most studies have focused on marker genes such as the 16S ribosomal RNA gene, which provide very efficient readouts of who is present in an environment, but assays such as shotgun metagenomics (which identifies all genes present in a given sample) or metabolomics (which identifies chemicals including those produced by microbial metabolism) are increasingly approachable and may provide a much richer picture. However, techniques that carry a risk of sequencing human DNA found in a given environment must be used with more caution in relation to human research ethics.

Appropriate environmental measurements to correlate with the human microbiota and health data include:

1) Assessment of airborne microbial biodiversity, perhaps including fungal and viral diversity. In general, outdoor air and indoor air differ substantially from each other (Kembel et al. 2012), and land use can also have a large effect on microbial sources in outdoor air (Bowers et al. 2011), with dog faeces being a substantial input in cities under some circumstances (Bowers et al. 2011).

2) Assessment of microbial biodiversity of homes and public places. Crowdsourcing can be an effective method for obtaining such samples, especially given the high public interest in such studies (Dunn et al. 2013).

a) Traditional versus microbiota-damaging building materials. Studies of the effects of building materials on environmental microbes, rather than on individual species of interest, are still very much in their infancy but are urgently needed.

b) Open windows versus air conditioning, and propagation of microbes from open windows through the rest of a building. Given increased automation of window shades and/or tinting for energy efficiency reasons, it may also be feasible to automate window opening at temperature-appropriate times to facilitate microbial exchange with the outdoors. It is also unknown whether exposure to beneficial microbes from the outdoors, or lack of ongoing exposure to largely human-derived microbes trapped indoors, explains more of the links between building microbes and human health.

c) City zones with and without green spaces. If green spaces have an effect, the effects of large parks versus small high quality green spaces, and the composition of trees, flowers and grass should also be assessed.

d) Dog parks, urban farms/petting zoos, and other sources of human–animal contact.

Compare farming methods:

a) Mono- versus poly-culture: Is the diversity of crops more or less important than which crop species are present? Does diversity within a species, e.g. growing multiple varieties of apples together rather than a monoculture, important?

b) Organic versus intensive chemical use. The effects of agricultural chemicals, including herbicides and pesticides, on leaf microbes or on soil microbes that are known to be immunomodulatory in humans are largely unknown.

c) Food in traditional farmers' markets versus modern supermarkets. These foods tend to vary along several dimensions including production methods, chemical inputs, amount of washing and remaining soil, and duration of storage, all of which likely affect the microbes.

6.3.2 Ways forward

Several remedies are also available from a policy perspective. Most urgently needed are global policies to preserve the biodiversity of the natural environment. These would include major restrictions on antibiotic misuse both in human and agricultural settings and possibly including antibiotic remediation of wastewater; assessing the effects of agricultural and building practices on microbes, perhaps including microbial biodiversity reserves in our houses, schools and offices, and identifying and preserving reservoirs of human-associated microbes in hunter-gatherer communities in Africa, Pacific Islands and South America, and ancestral reservoirs of microbes in the Great Rift Valley that represent the microbial heritage with which our species coevolved. City planning and architectural designs that optimize biodiversity of microbial exposure in urban settings are also needed, including green spaces, opportunities for contact with microbes from wildlife and farm animals, and modified air conditioning strategies that spread beneficial microbial diversity rather than *Legionella*. Finally, a broad-scale education initiative, including citizen-science efforts parallel to those employed by American Gut (where members of the public can both act as subjects and participate in an open data analysis effort) and MOOCs (massive open online courses), as well as more traditional classroom and online resources aimed at children, educators, physicians, politicians, the press, advocacy organizations, and members of the general public will be needed both to communicate the results obtained to date in this exciting field and to lay the groundwork for appropriate assimilation and deployment of new findings in this rapidly evolving field.

9. Biodiversity and biomedical discovery

1. Introduction

The diversity of life on earth has been an engine of biomedical discovery and sustained human health for millennia, contributing to countless medical advances. Ironically, in many instances, the very organisms that have given humanity vital insights into human diseases, or are the sources of human medications, are endangered with extinction because of human actions. While other sources explore these subjects in detail (see Chivian and Bernstein 2008), this chapter briefly explores the substantial contribution of biodiversity to biomedical discovery, and discusses key health challenges posed by accelerating rates of biodiversity loss.

2. Why biodiversity matters to medical discovery

Many of the diseases that afflicted or killed most people a century ago are today largely curable or preventable. How did this happen? Applying scientific methods to medical research certainly contributed to this development, as did the engagement of many researchers and medical professionals. However, no amount of scientific rigour, researchers, or any other factor could suffice on its own to reduce the human suffering realized in the twentieth century, as many of these developments depended, wholly or in part, on biological diversity (Chivian and Bernstein 2008).

Antibiotics rank among the most significant breakthroughs that have considerably improved human health in the twentieth century. Death from pneumonia was so prevalent in the early twentieth century, for instance, that Sir William Osler described it is as the "captain of the men of death" (see, for example, Barry 2005). With the arrival of penicillin and its descendants, rates of death from pneumonia plummeted (see, for example, Podolsky 2006). The penicillins as well as nine of the thirteen other major classes of antibiotics in use derive from microorganisms. Between 1981 and 2010, 75% (78 of 104) of the antibacterials newly approved by the United States (US) Food and Drug Administration can be traced back to natural product origins (Newman and Cragg 2012). Percentages of antivirals and antiparasitics derived from natural products approved during that same period are similar or higher. The over- and misuse of antibiotics has cultivated a slew of highly resistant bacterial strains, which in some instances cannot be effectively treated with any currently available antibiotic (Levy and Marshall 2004; Davies and Davies 2010). A race to find new antibiotics to overcome so-called superbugs ensued (e.g. Spellberg et al. 2008). As of February 2014, at least 45 new antibiotics that carry the potential to treat serious bacterial infections are in development for use in the US. Most of these rely upon a natural product predecessor (Pew Health Initiatives 2014).

For as long as we know, humanity has relied upon compounds from nature designed to treat what ails us (see also the chapter on traditional medicine in this volume). Otzi, the oldest known natural mummy, who was found under a thawing glacier in the Italian Alps, died more than 5000 years ago and carried with him a pouch that contained birch polypore fungus *Piptoporus betulinus* known to reduce inflammation and kill bacteria (see, for example, Bortenschlager and Oeggl 2000). Reliance upon biodiversity for new drugs continues to this day in most domains of medicine. More than half of the 1355 newly approved drugs by the US Food and Drug Administration between 1981 and 2010 had natural product origins (Newman and Cragg 2012).

The success of drug development from natural products manifests the common molecular currency of life on earth. Species as diverse as *Conus geographus*, *Penicillium citrinum* and *Taxus brevifolia* – a meat-eating marine snail, rice fungus and boreal conifer – produce molecules that in humans relieve pain, reduce cholesterol, and treat breast, ovarian, lung and other cancers, respectively, because organisms, as diverse as they are, communicate within themselves and other creatures using common molecular currencies (Chivian and Bernstein 2008). As discussed in the chapter on traditional medicine, this often increases the appeal for bioprospecting for medicines.[1]

While most of the medicinal potential of nature has yet to be tapped, we may be losing potential new cures with biodiversity loss. One of several examples is the two species of gastric brooding frogs indigenous to the rainforests of Queensland, Australia. These species employ perhaps the most unusual reproductive strategies in the animal kingdom, using their stomachs as wombs for their young (Chivian and Bernstein 2008; McNeely 2006). Having gone extinct in the 1980s, their unique reproductive physiology was lost with them, which could have alleviated the suffering of tens of millions of worldwide who have peptic ulcer disease and related disorders.

Plants have been the single greatest source of natural product drugs to date, and although an estimated 400 000 plant species populate the earth, only a fraction of these have been studied for their pharmacological potential (Hostettmann et al. 1998). For example, one of the largest plant specimen banks, the natural products repository at the National Cancer Institute, contains ~60 000 specimens (Beutler et al. 2012). The same number of species – 60 000 – are thought to be used for medicinal purposes worldwide and perhaps as many as 40% of these species are considered threatened with extinction (Biodiversity Indicators Partnership 2010; CBD 2014; see also the chapter on traditional medicines in this volume).

Plant species as diverse as the Himalayan yew, *Taxus wallichiana* (and other *Taxus* spp.) or African cherry, *Prunus africana*, long used in traditional medicines, have been threatened by factors such as overharvesting and international trade, driven by high consumer demand (Hamilton 2003). Both are listed under the Convention of International Trade in Endangered Species of Flora and Fauna (CITES). The establishment and enforcement of effective management and trade of wild-collected species, both by governments and corporations, remains a critical need in plant conservation (e.g. Phelps et al. 2014).

Other realms of the living world, especially the microbial and marine, are almost entirely unstudied and hold vast potential for the development of new drugs, given both their diversity and the medicines already discovered from them (Chivian and Bernstein 2008).

1 For further discussion on marine bioprospecting see, for example, Hunt and Vincent (2006).

Case study: *Aplysia californica* and the human brain

Drugs derived from natural products may perhaps be the most direct and concrete bond that many may find between biodiversity and medicine. However, biodiversity holds much broader connections with human health. In many arenas of biomedical inquiry, biodiversity has beenan invisible linchpin of discovery. For example, of the 104 Nobel prizes in Medicine awarded since Emil von Behring received the prizein 1901 for his research on guinea pigs to develop a treatment for diphtheria, 99 were given to scientists who either directly or indirectly made use of other species to do their research.

In 2000, Eric Kandel shared the Nobel prize in Physiology or Medicine with Arvid Carlsson for his groundbreaking research on memory. Kandel's research established, at a cellular and molecular level, how our brains learn and form memories. He did not study human brains to do this. Instead, he studied the nervous system of sea hares from the genus *Aplysia*. A human brain has about 86 billion neurons whereas *Aplysia* has, all told, around 20 000, and only about 100 of those neurons are involved in memory. In addition, *Aplysia's* memory cells are also among the largest of their kind in the animal kingdom and can be visualized with the naked eye. This makes monitoring the electrical messages that scurry across their membranes, and exploring how these messages may alter genes and other molecules that control a neuron's inner workings, comparatively easy. With these advantages, Kandel found what was difficult, if not impossible, otherwise. What was gleaned from *Aplysia's* nervous system made possible further research in other species, which has deepened our understanding not only of learning and memory, but of a host of human ailments, from substance abuse and Alzheimer disease to the lifelong consequences of early childhood trauma.

For more on research from *Aplysia* see: Kandel ER. (2007). In search of memory: the emergence of a new science of mind. New York, USA: WW Norton & Company.

FIGURE 1: *Aplysia californica* releasing ink that not only clouds predators' view but masks their sense of smell and taste.


GENEVIEVE ANDERSON

Case study: *Thermus aquaticus* and DNA research

Thermus aquaticus is another behind-the-scenes, though absolutely vital, species for biomedical discovery. This bacterium was first identified in the Mushroom Spring of Yellowstone National Park in 1966 as part of an expedition to find life in places where it was not supposed to exist. The late summer day that Thomas Brock and Hudson Freeze collected samples from Mushroom Spring, the water temperature measured 69 ºC.

At first, *T. aquaticus* was little more than a curiosity: an organism able to live at temperatures that would cook most cells, including human cells. This reputation soon changed. Advances in the early years of genetic research were many but were limited in part by difficulties with replicating DNA in a laboratory. All life replicates DNA in order to survive. To do this, paired strands of DNA are separated and then copied using a specialized molecular copying machine known as DNA polymerase.
To separate the DNA strands, cells use a set of molecular machines. Using these machines in a laboratory proved too difficult, so scientists turned to another method, heat. DNA strands reliably separate at temperatures just over 90 ºC and remain separate at around 70 ºC, right near the optimal temperature for *T. aquaticus* and its DNA polymerase known as *Taq*. The ability of *Taq* to copy DNA at high temperature forms the foundation of the polymerase chain reaction, or PCR, which is arguably the single most important tool in genetic research ever invented. In 2013 alone, nearly 27 000 articles make reference to PCR in the US' National Library of Medicine's PubMed database.

Just as with the ability of natural products obtained from one species to exert influence on many others, the ability of *Taq* to work on DNA from multiple species underscores how all life shares some basic features. At the same time, *Taq* also speaks of the importance of the diversity of life. Without life thriving at high temperatures, there would be no polymerase suitable for PCR and, without PCR, the modern-day genetic research juggernaut may never have got off the ground.

Source: Brock and Freeze (1969)

3. Biodiversity, the microbiome and antimicrobial resistance

Far greater than what individual species offer to medicine through molecules they contain or traits they possess, an understanding of biodiversity yields irreplaceable insights into how life works, which bear upon current epidemic diseases. Consider the multiple pandemics that have resulted from antimicrobial or antibiotic resistance (see also the chapters on infectious disease and health care and pharmaceuticals in this volume). Human medicine tends to use a paradigm for treating infections unknown in nature, which is treating one pathogen with one antibiotic. Most multicellular life (and a good share of single cellular life) produces compounds with antibiotic properties but never uses them in isolation. Infections are attacked, or more often prevented, through the secretion of several compounds at once.

Antibiotic use, aside from its potential to cultivate resistance, also carries the potential to disrupt relationships between hosts and their symbiotic microbes. The human microbiome contains tenfold more microorganisms than cells that comprise the human body, and antibiotic use can dramatically alter its composition and function (Cho and Blaser 2012). Although much of the microbiome and its relationship to its host remains unknown, it is already apparent that changes to the variety and abundance of various microorganisms, as can occur with antibiotic use, may affect everything from the host's weight and the risk of contracting autoimmune disease, to susceptibility

FIGURE 2: Mushroom Spring in Yosemite National Park. In this sulphurous hot spring was discovered *Thermus aquaticus*, the source of *Taq* polymerase, which serves as the essential cog in the polymerase chain reaction, arguably the single most important method used in genetic research.


JIM PEACO / US NATIONAL PARK SERVICE

to infections (Petersen and Round 2014). The microbiome may also shape mood and behaviour (see also the chapter on microbial biodiversity and noncommunicable diseases in this volume). The influence of microorganisms on the larger life forms they cohabit is not terribly surprising, given the history of life on earth. Several billion years elapsed between the appearance of the first single-celled creatures and multicellular life, and single-celled creatures appear to have enmeshed themselves with all their multicellular successors.

4. Future challenges: implications of biodiversity loss for medical discovery

In this time of technological advancement, when the precision of measurement comes at increasingly diminutive scales such as nanoseconds or nanometers, and we begin to explore the most minute forms of life on earth, we have at best a first approximation of the numbers of organisms we share the planet with (May 1988; Mora et al. 2011; Costello et al. 2013). About 2 million of an estimated 10 million species on earth have been given scientific names (Wilson 2003). For many of these, we know little more than their names as they are known from only a single encounter in which an explorer observed a creature never before seen. Most of life's diversity, however, cannot be seen by the naked eye, and of these microscopic creatures, we know far less.

Even with this limited view of the life we share the planet with, we know that each year the variety of organisms on earth continues to decline (CBD 2014). Recent scientific estimates indicate that species are disappearing up to 1000 times faster than occurred before humanity populated the planet (CBD 2010). Such statistics are often difficult for many people to grasp, especially as most loss of biodiversity goes unnoticed. While each of us may in our own lifetimes recognize that one, or even a few, species that were once common in a place we know have disappeared, far more often species vanish without notice.

In the coming decades, a great mass of life on earth hangs in the balance for survival as pressure on the biosphere mounts, primarily from habitat loss and, increasingly, climate change (see also the chapter on climate change in this volume).

5. Ways forward: conservation as a public health imperative

Too often, biodiversity harnessed from one corner of the earth has benefited another corner, with little payback to its origins. Existing frameworks, such as the Nagoya Protocol (see http://www.cbd.int/abs/about/) or Fairwild Standard (see http://www.fairwild.org), seek to ensure that biodiversity's value accrues in its place of origin. These mechanisms, if successfully implemented, could drive large investments in conservation where biodiversity is richest and most imperilled. Happily, successes have already been had in India and Viet Nam for plant bioprospecting and in Kenya, Kazakhstan, Bulgaria and Poland for certification of exported goods (see, for example, Krishnakumar 2012; Meijaard et al. 2011).

As this volume attests, we know astonishingly little about the life forms that inhabit the earth. Even so, we know that many have already provided invaluable cures for human diseases and tremendous insights into the workings of the human body. Given our ignorance of biodiversity, we would be foolish to try to conserve only what we deem important to ourselves. The dividends of biodiversity realized in our economies must be widely shared to promote the conservation of biodiversity where it is needed the most (Pimentel et al. 1997; Sukhdev 2014).

As compelling as arguments of the past have been to conserve biodiversity, rates of extinction are accelerating largely due to habitat destruction and, increasingly climate change (e.g. CBD 2014; Urban 2015; Pounds et al. 2006; Franco et al. 2006). To stem the tide of biodiversity loss, innovative methods must be used to convince policy-makers and the citizens of the world that biodiversity must be saved.

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10. Biodiversity, health care & pharmaceuticals

1. Introduction

Other chapters of this state-of-knowledge report explore the role that biodiversity plays in shaping public health outcomes – including relationships with infectious diseases, noncommunicable diseases, and trauma associated with natural and human-induced disasters. The contribution of these chapters to understanding how population health and the delivery of primary health care are influenced by biodiversity is a central objective of this state-of-knowledge review. However, to gain a complete understanding of the health–biodiversity nexus, it is also important to recognize that policies and practices associated with the delivery of health care can have impacts on biodiversity and the sustainability of ecosystem services, and that these impacts can subsequently have a negative effect on human health. Impacts can occur from a number of sources, including health care-associated manufacturing, health-care and health research facilities (hospitals, clinics, etc.), and health-care related transport and trade. Potential environmental concerns include energy demand; emissions to the atmosphere, soil and water; water use; waste disposal, including potentially hazardous wastes; and the extraction/harvesting of wild species for drug exploration or use. Box 1 below provides an overview of some of the major environmental considerations associated with the delivery of health care.

A wide range of chemical substances is used to support health care, including pharmaceuticals, disinfectants, cleaning products, X-ray contrast media, various personal care and hygiene products, and excipients. It is inevitable that these will sometimes be released into the natural environment through their manufacture, use or disposal, and that they could subsequently affect biodiversity. Of particular interest, due to their biological activity, are pharmaceuticals. Since at least the early 1990s, there has been increasing concern over the potential impacts of pharmaceuticals used in health care on the natural environment (Halling-Sørensen et al. 1998; Daughton and Ternes 1999; Kümmerer 2009).

The particular focus of this chapter is the issue of the environmental side-effects of medication – the potential impacts that drug entities and related chemical compounds may have when they enter the environment. The presence of pharmaceuticals in the environment is an issue that has received a great deal of scientific attention since the 1990s, and numerous studies have now been performed aimed at assessing and understanding their environmental occurrence (i.e. how and to what extent these compounds enter the environment), fate (what happens to these compounds after release), and effects (particularly ecological and (eco)toxicological impacts). There is increasing evidence that pharmaceuticals in the environment

Box 1. Overview of some of the major environmental considerations associated with the delivery of health care

Examples of potential impacts of health-care activities on ecosystems

Issue	Example	Potential impacts
Energy use	Energy demand for health-care facilities can be significant, with 24-hour requirements for medical equipment, lighting, heating and air-conditioning.	Energy demand is associated with the consumption of fossil fuels, emission of greenhouse gases and other pollutants.
Water use	Hospitals and other health-care facilities can use large quantities of water, particularly for patient hygiene, surface cleaning, food preparation and general sanitation.	This adds significantly to community demand for water resources, potentially impacting on aquatic ecosystems or water-dependent habitats.
Water quality	Health-care facilities use significant amounts of a wide variety of pharmaceuticals and personal care products (PPCPs), as well as sanitizers, and other chemicals, such as X-ray contrast media. Many of these are not fully degraded by modern wastewater treatment systems and end up in natural waters.	Release of PPCPs into the soil or aquatic environments, including some that act as endocrine-disrupting compounds, is implicated in a range of impacts upon ecosystems and upon animal health and behaviour.
Waste production	As well as large quantities of general paper and plastic waste, health-care facilities can produce large quantities of food waste and hazardous waste materials, including biohazardous and radioactive substances.	Waste disposal poses challenges for environmental and public health authorities. Inappropriate waste management and disposal infrastructure can impact the quality of water, soil and air, and affect human, plant and animal health.
Air quality	Many hospitals have incinerators to deal with hazardous and/or biological waste, which may release contaminants into the local atmosphere. Emissions associated with health-care-associated transport can also be significant.	This has potential for local impacts on human or ecological health (e.g. from NO_x, SO_x, particulates, heavy metals), as well as the wider release of greenhouse gases.
Medicinal species harvesting, medical research and drug discovery	Much modern and traditional health care depends on medicines derived from nature, from modern drugs to herbal remedies and complementary therapies. Modern medicine also utilizes wild and captive species for animal studies.	Unsustainable exploitation of biodiversity for medicinal use or research can endanger species and ecosystems, and threaten the well-being of the human communities they support.

Source: Adapted from COHAB 2014

can have an adverse effect on biodiversity and ecosystem services, unintentional though these may be. Where these effects on ecosystems could lead to downstream effects on public health, interventions initially intended to promote public health (i.e. the manufacture, supply and use of pharmaceutical products) may actually have unforeseen indirect negative impacts on health and well-being.

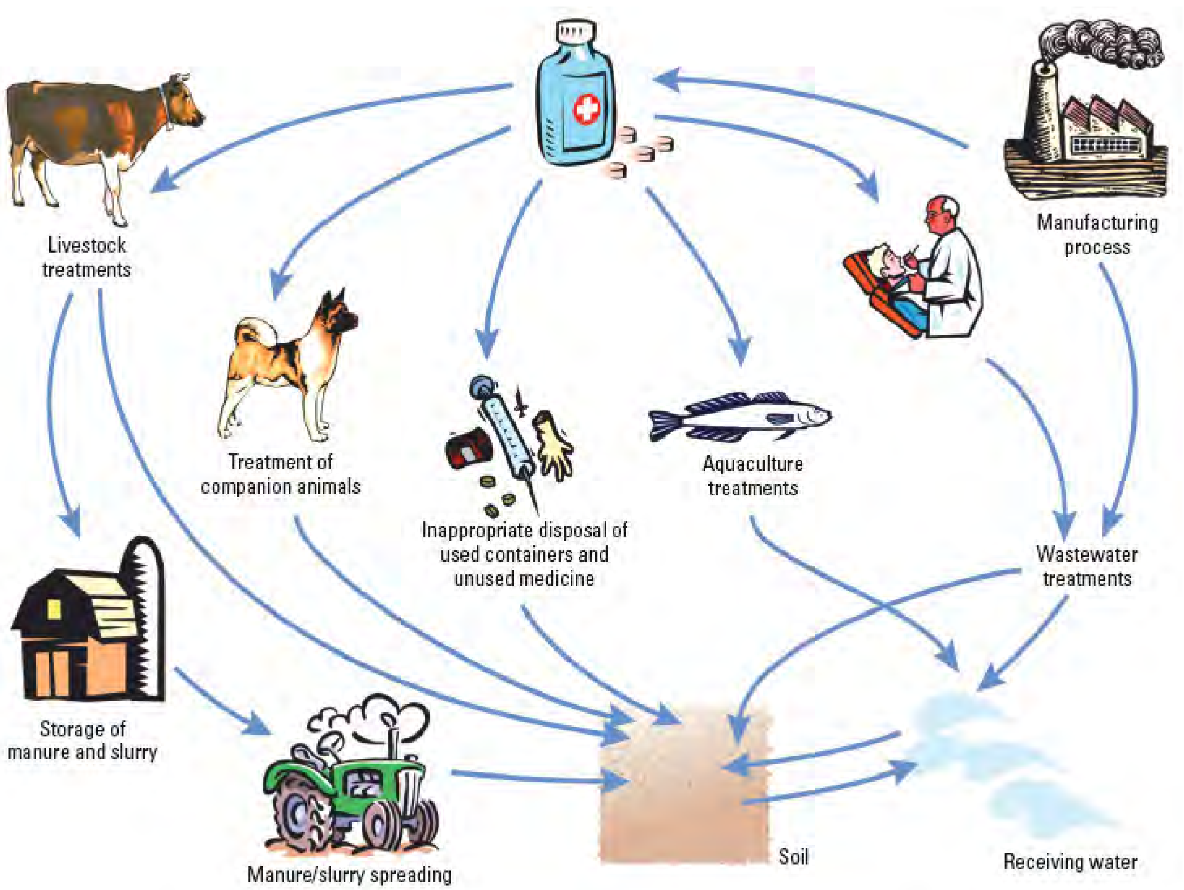
The issue of pharmaceuticals in the environment has come under the scrutiny of regulatory bodies, including drug approval agencies such as the United States (US) Food and Drug Administration and the European Medicines Agency of the European Union (EU), and others (Breton and Boxall 2003; Kampa et al. 2010; Küster and Adler 2014). It is also of particular interest to the pharmaceutical industry, with many major drug firms engaging with environmental chemists and regulators in order to understand and address these issues (Taylor 2010). As such, the issue of pharmaceuticals in the environment illustrates an important opportunity for collaboration between health and environmental scientists, regulators and the private sector to tackle a critical, cross-cutting issue.

In the sections that follow, evidence for the inputs and occurrence of pharmaceuticals in the environment, and the potential impacts of these on biodiversity is explored. Approaches for reducing these inputs and impacts are also discussed.

2. Inputs and occurrence of active pharmaceutical ingredients (APIs)

Although pharmaceutical products have probably been entering the environment for as long as they have been manufactured and used, this topic has begun to receive considerable

FIGURE 1: Major pathways of release for active pharmaceutical ingredients into the environment



Source: Reproduced from Boxall (2004) with permission from EMBO Reports attention only in recent years, as advances in environmental monitoring technologies and a greater awareness of environmental risk has promoted their detection and assessment. It is inevitable that during the life-cycle of a pharmaceutical product, active pharmaceutical ingredients (APIs) are released into the natural environment (Halling-Sørensen et al. 1998; Daughton and Ternes 1999; Boxall 2004). APIs can be released to rivers and streams during the manufacturing process – either directly through fugitive (accidental or unmanaged) emissions, or to wastewater treatment plants. Emissions from manufacturing can be particularly high in developing regions with a high manufacturing base and with limited regulation (Larsson et al. 2007; Fick et al. 2009; Cardoso et al. 2014).

APIs also enter sewerage systems through human use (Santos et al. 2010); API molecules may be incompletely metabolized or broken down in the body, and whole compounds or their metabolites, daughter compounds (which are also sometimes referred to as transformation products) may be released with domestic wastewater. Following use, in areas with sewerage connectivity, human-use APIs and their metabolites will be excreted to the sewerage system and transported to wastewater treatment plants. The complexity of some pharmaceutical molecules can limit their degradation in wastewater treatment plants, with the result that APIs and their transformation products can be discharged to the environment in the final effluent (treated water) when it is released to surface waters such as rivers and streams. In areas with low sewage connectivity, APIs will be released directly to the environment. Human-use APIs may also be released into the soil environment when contaminated sewage sludge or sewage effluent is applied to land. These may then be transported to groundwater and surface waters through leaching, land drainage and storm run-off. By these routes, APIs can also enter water resources used for drinking water supply. Drinking water treatment systems may not effectively remove these compounds, and APIs have been found in treated drinking water, albeit at very low (ng/L) concentrations. From a toxicological perspective, several detailed risk assessments have determined that public health risks from the consumption of individual APIs via drinking water are likely to be very low (Bruce et al. 2010; WHO 2011). However, the effects of this exposure route are difficult to evaluate, and there have been few studies of the potential risks from long-term exposure to mixtures of APIs in drinking water (Smith 2014). Risks to certain vulnerable groups require further assessment (Collier 2007).

It is therefore not surprising that a range of human APIs, including hormones, antibiotics, non-steroidal anti-inflammatory drugs (NSAIDs), antidepressants and antifungal agents have been detected in rivers and streams across the world (Hirsch et al. 1999; Kolpin et al. 2002; Monteiro and Boxall 2010).

In contrast, veterinary APIs (i.e. pharmaceuticals used for treating animals) can enter the environment more directly, for example, by being excreted directly into the soil by pasture animals (Boxall et al. 2004), or directly applied to surface waters and marine habitats in aquaculture operations, with a risk of a build-up in sediments (e.g. Coyne et al. 1994; Daughton and Ternes 1999; Rico and Van den Brink 2014). In terrestrial ecosystems, the use of pharmaceuticals in livestock is likely to be the most significant source of veterinary APIs entering the environment (including via spreading of manure or slurry as fertilizer). However, the use for treatment of domestic pets, wildlife and feral animals may also be important. Of particular interest in this regard may be long-term, widespread programmes for eradication of wild animal diseases through baiting programmes, which run the risk of dosing non-target animals directly (see, for example, Hegglin et al. 2004; Campbell et al. 2006). A range of veterinary APIs have consequently been detected in agricultural soils, in marine sediments, and in surface waters receiving run-off from farmland (Boxall et al. 2004). In addition to the manufacture and normal use of APIs, environmental inputs can also arise from their disposal, either through domestic refuse or disposal to the sewer system. Landfill sites have been shown to be a potentially important source of API contamination in surface and groundwater (Bound and Voulvoulis 2005; Musson and Townsend 2009).

While the reported concentrations of APIs are generally low (i.e. <µg L 1 in surface waters), these substances have been observed across a variety of hydrological, climatic and land-use settings. It is also known that some substances (e.g. the tetracycline and fluoroquinolone antibiotics, selected antiepileptics and some antidepressants) persist in the environment for months to years (e.g. Boxall et al. 2006; Kay et al. 2004), meaning that organisms can be exposed to these compounds throughout their lifetime.

3. Impacts of pharmaceuticals on biodiversity and ecosystem services

APIs are developed and used because of their biological activity. While in many cases the modes of action of APIs are well established, for many drugs the mechanism of action is not specifically known or fully understood. This is true of human and veterinary APIs. Most pharmaceuticals are designed to interact with a target (such as a specific receptor, enzyme or biological process) in humans and animals to deliver the desired therapeutic effect. If these targets are present in organisms in the natural environment, exposure to some pharmaceuticals might be able to elicit effects in those organisms. Pharmaceuticals can also cause side-effects in humans and it is possible that these and other side-effects can also occur in organisms in the environment.

It is also possible that metabolites and other transformations products of APIs can have similar or entirely different biological activity in exposed biota (Daughton and Ternes 1999). While the individual or incidental exposure concentrations of selected APIs may be very small, in some instances, the exposure may occur over a long period, particularly where APIs are persistent, or where they are routinely emitted. Furthermore, in ecosystems receiving a combination of APIs, e.g. in sewage treatment plants receiving water or sediment around fish farms, populations of wild species are exposed to multiple different APIs and transformation products, leading to the risks of additive effects (caused by exposure to different

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APIs with similar modes of action) or synergistic effects (interaction between different APIs). The kinds of potential impacts range from acutely toxic events, including death for some species (notably invertebrates), and sublethal impacts, including behavioural, endocrine, immunological, reproductive and mutagenic effects. This often occurs in a context where wildlife is exposed to other forms of pollution or disturbance, so that APIs should be seen as adding to a larger environmental burden.

Evidence for the ecotoxicological impacts of even very low concentrations of APIs in the environment has been noted in some studies. For human APIs, a major area of concern is the impact of synthetic hormones and hormonally active pharmaceutical compounds. These add to an already significant environmental burden of endocrine-disrupting compounds (EDCs), which comprise a wider range of chemicals, including various detergents, flame retardants, pesticides, plant hormones and others, as well as naturally occurring hormones that enter sewage treatment works. The ecological impacts of EDCs as a wider group of substances include the occurrence of intersex characteristics in male fish; this can be persistent and irreversible, with subsequent impacts on fertility and population stability (Orlando and Guillette 2007). These effects have been particularly noted in aquatic ecosystems, where eggs can develop in the testes of male fish exposed to EDCs. There is a large body of evidence that suggests that one particular API, ethinylestradiol (EE2) plays a significant role even at very low environmental concentrations. EE2 is the active ingredient in the human contraceptive pill, which is used by approximately 100 million people worldwide (Jobling and Owen 2012). As well as it use in birth control, EE2 is also used for the treatment of various gynaecological and endocrine disorders. Laboratory research has shown that environmentally relevant concentrations of EE2 alone can have dramatic impacts on wildlife (Lange et al. 2001; Nash et al. 2004), while in one study in Canada, involving the introduction of EE2 in a lake at a concentration of just 5 parts per trillion (which is only slightly higher than the concentrations expected in rivers and streams) led to the complete collapse of an entire population of fish (Kidd et al. 2007).

Another class of human APIs of current concern is the antidepressants, which include compounds such as fluoxetine, escitalopram and paroxetine. Recent research has suggested that environmentally relevant concentrations of fluoxetine, linked to concentrations released in coastal and estuarine habitats in the United Kingdom (UK), cause a change in behaviour of the marine amphipod *Echinogammarus marinus* by altering levels of serotonin. Exposed amphipods showed an increased tendency to swim close to the water surface, which increases the likelihood of predation by fish or birds (Guler and Ford 2010). Bean et al. (2014) also demonstrated that environmentally relevant levels of fluoxetine could have significant behavioural and physiological effects on starlings (*Sturnus vulgaris*), which could be exposed to the drug when feeding at sewage treatment plants or fields treated with sewage sludge. Recent research has also indicated that environmentally relevant levels of antidepressants can affect the reproduction, feeding and predator-avoidance behaviours of fathead minnows (Weinberger and Klaper 2014). Brodin et al. (2014) demonstrated that low μg/L levels of the anxiolytic oxazepam in freshwater could lead to bioaccumulation in the predatory European perch (*Perca fluviatilis*), with significant impacts on feeding behaviour.

Impacts on wildlife have also been noted for veterinary APIs. For example, Floate et al. (2005) provide a comprehensive review of studies on parasiticides applied to pasture animals. These show that some classes of APIs are excreted to pasture environments in concentrations that can be lethal to coprophagous (dung-eating) insects and to other species inhabiting the pasture soil environment, over periods ranging from a few days to several months (see also Lumaret et al. 2012). This poses a potential risk to other species through the food chain, including bats and birds. While evidence for the direct toxicity of environmental concentrations to vertebrate predators of pasture insects has not been determined, there is concern that reductions in farmland invertebrates may lead to locally significant reductions in prey availability, including important prey items for certain species (e.g. Vickery et al. 2001; Wickramsinghe et al. 2002; Boxall et al. 2007).

Perhaps the most well-known incidence of veterinary drug impacts on wildlife have been associated with the declines of several species of vultures in South Asia (see case study below), resulting from the use of the pharmaceutical diclofenac in veterinary preparations, leading to near-extinction of once-abundant wildlife, with

Case study: diclofenac and decline in the population of vultures

The Indian subcontinent was once home to several million vultures. These birds played a vital role in the ecosystem, cleaning up carcasses of dead animals, and thereby helping to reduce the risk of disease and contamination of soil and water resources. Their numbers were supported by the huge numbers of livestock; India alone has the largest cattle population in the world. Dead livestock are usually left out in the open for removal by vultures – the quickest, cheapest and most efficient natural disposal method. But a drastic decline in vulture numbers began in the 1990s. The three most abundant species – the oriental white-backed vulture (*Gyps bengalensis*), the Indian vulture (*G. indicus*) and the slender-billed vulture (*G. tenuirostris*) declined by more than 95% in Pakistan, India and Nepal between 1990 and 2001. It became evident that the decline in vulture numbers was having an impact on ecosystem functioning, as evidenced by the number of animal carcasses that were left to decay in fields across the Indian subcontinent. This has helped to boost numbers of feral dogs, rats and other scavengers, resulting in a greatly increased threat of rabies and other diseases in the human population.

Postmortems on vulture carcasses determined that massive numbers of vultures were dying from visceral gout – the accumulation of uric acid deposits associated with kidney failure, but microbiological and toxicological studies failed to pinpoint the cause as the decline progressed. Eventually, an investigation of the primary food source of *Gyps* vultures – livestock carcasses – led to the identification of a pharmaceutical compound, diclofenac sodium, as the cause. Diclofenac has been widely administered by veterinarians and famers in analgesic, antirheumatic and antimicrobial preparations, and its availability increased greatly in the early 1990s due to numerous market factors. There have been reports of widespread abuse of the prescription laws that should restrict drug sales, with poor dose controls for humans and livestock. This drug has been shown to be highly toxic to vultures at the levels to which they are exposed from livestock carcasses. Diclofenac has been banned in India, Pakistan and Nepal since 2008; however, there is concern that the ban is being circumvented or ignored in some areas, and more widespread controls are required, as well as greater cooperation with the farming community, if vulture populations are to recover in the region.

Studies have shown that African *Gyps* vultures are equally vulnerable to diclofenac poisoning, suggesting that the risk may extend to all *Gyps* species, and there are concerns that many other scavenging bird species are also susceptible. With the recent controversy over the approval of diclofenac for veterinary use in parts of Europe, including Spain, which is internationally important for avian scavengers, it is clear that there is a need for environmental risk assessments of veterinary medicines to take a multidisciplinary perspective, based on the full scope of scientific evidence, and for regulatory authorities to take necessary precautions to prevent environmental contamination with veterinary APIs.

Sources: Oaks et al. 2004; Markandya et al. 2008; Cuthbert et al. 2011; Naidoo et al. 2009; Margalida et al. 2014 several potential knock-in impacts on human well-being, including increased public health risks.

Although numerous detailed risk assessments suggest that environmental concentrations of most APIs in isolation are unlikely to have any significant impact on biodiversity, these examples illustrate that there is reason for concern; there is a need for more integrated environmental risk assessments that account for ecological interactions, and more effort is needed to understand the risks associated with mixtures of APIs in the environment (Backhaus 2014).

Another issue of concern related to both human and veterinary APIs in the environment, with more widespread implications for human health, is the link to the growing threat of antimicrobial resistance. The number and diversity of drug-resistant pathogens is increasing, and a slowdown in the production of new antimicrobial drugs since the 1980s means that existing treatments are increasingly ineffective against several important human diseases (WHO 2014). Research has shown that drug-resistant infections accounted for a large number of emerging infectious diseases in the past 30 years, and that multidrug resistance (when an infection shows resistance to a range of drugs normally used to treat it) is a serious and growing concern (Jones 2008; Levy and Marshall 2004). The causes of antimicrobial resistance are complex, and although genes for antibiotic resistance occur widely in nature without human influence, the inappropriate use and overuse of antimicrobials, including the non-therapeutic use of antibiotics as growth promoters in agriculture, is a major cause of drug resistance (WHO 2012). The risk of resistance is also increased by the routine disposal of drugs and drug residues. The release of antimicrobial drugs into the environment from human use and manufacturing, veterinary applications, disposal at landfill sites, or use in aquaculture increases the exposure of microbes to those drugs, and thereby increases the potential for the development of drug resistance. Research has shown that pollution and patterns of human water use are important risk factors (Pruden et al. 2012, 2013; Wellington et al. 2013), and that drug-resistant microbes are found in nature and can be carried by wildlife, particularly by animals associated with agriculture or human settlements (Radimersky et al. 2010; Taylor et al. 2011; Carroll et al. 2015), and persist in agricultural soils (Kyselková et al. 2015).

4. Future challenges: effects of social and environmental changes

The range of factors affecting the occurrence of APIs in the environment is by now well understood. The science of risk assessment for these pollutants is also increasingly advanced, with product risk assessment based on product usage (or estimated usage for novel drug entities), estimates of wastage, (bio)degradation studies, and assessment of ecological toxicity. However, a number of important issues surrounding inputs to the environment remain to be addressed.

For example, changing demographics are likely to significantly alter the type, range and quantities of APIs being utilized at the local and regional levels. For human APIs, ageing populations, increased migration, economic transitions in developing countries, and urbanization are all likely to see shifts in the use profiles of pharmaceutical products. Changes in agricultural practice – to accommodate the increased demand for specific foods, including responses to nutrition transitions and conversion of natural habitats for food production – are likely to see changes in the quantities and kinds of animal health products in use. Climate change is also expected to have an impact by affecting the ecology of various pathogens in humans, domestic animals and wildlife, and thereby potentially leading to demands for the increased use of certain drugs, and development of new drug entities to address increased or emerging health threats. Climate change may also affect how APIs occur in the environment and their relative risks to biodiversity. For example, changes in surface water run-off, changing water and soil temperatures, and changes in natural vegetation and wildlife populations may be expected to affect the movement and degradation of APIs in the environment, their bioavailability, and the types of species exposed to different API compounds. Therefore, further work


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is required to understand the routes of exposure of wild populations to APIs, and how these might change under different scenarios of future climate and population changes (Boxall et al. 2008; Kim et al. 2010; Redshaw et al. 2013).

To date, much of the research into the environmental occurrence, fate and effects of APIs has been focused on high-income countries, and more research effort is needed to understand the situation in least-developed countries, and to devise solutions to related environmental risks (Kookana et al. 2014). Risk assessments also need to be strengthened to better account for the sublethal effects of APIs on wildlife populations (e.g. in situations of low dose but long exposure), particularly those that may have knock-on effects on predator–prey relationships and wider food chain impacts. The potential risks of synergistic or additive impacts – through combinations of APIs in the environment, or co-occurrence with other pollutants (e.g. the added impacts of EE2 in populations also exposed to other endocrine-disrupting compounds) – also need to be better understood (Backhaus 2014).

One of the most pressing concerns involves the manner in which antibiotic, antifungal and antiparasitic APIs in the environment may present selection pressures for drug resistance in pathogenic organisms. The increasing threat of antibiotic resistance, including the emergence and rapid spread of multidrug resistance, means that there is a demand for novel drug responses as well as for a greater understanding of how the use, abuse or overuse, and disposal of existing antimicrobials might promote the emergence and spread of drug resistance. Related to this is the need for further research on how other forms of pollution may enhance selection pressure for the development of antibiotic resistance in environmental microbes (Baker-Austin et al. 2006; Finley et al. 2013), and on how drug-resistant pathogens may be spread by wildlife.

Additional work is also required to prioritize APIs for more detailed risk assessment. For example, which types of drugs are likely to enter the environment in ecologically significant quantities? It is estimated that over 4000 different pharmaceutical compounds are currently in widespread use (Boxall et al. 2012) and the majority of these have not been tested for the environmental effects. While new pharmaceutical products are subjected to risk assessment, it is unlikely that a significant proportion of the existing APIs can be subjected to full risk assessment in a timely manner. It is important therefore that priority API pollutants are identified for study.

5. Ways forward: reducing the impact of APIs in the environment

In most developed countries with strong regulatory systems for integrated prevention and control of pollution, it has long been considered that outputs of waste and wastewater from the manufacture of APIs are well regulated and controlled, so that fugitive emissions of APIs to soil, groundwater and surface water would be minimal – not least because any significant fugitive loss of API from a manufacturing facility also represents a potential loss of revenue. However, research into the environmental burdens of APIs from sewage treatment plants receiving effluent from pharmaceutical factories has suggested that manufacturing facilities are a potentially significant source of API inputs to surface water and sewage sludge (Philips et al. 2010; Cardoso et al. 2014). In some developing countries, environmental inputs from manufacturing sites have been found to be very high, particularly in areas with weak or no regulatory frameworks or poor enforcement, and in areas with high concentrations of API factories (Fick et al. 2009; Larsson et al. 2007; Larsson 2010).

Therefore, it is important that greater efforts are made to understand, regulate and minimize the potential for API release from the manufacturing sector, particularly in developing countries. This should include advancement and uptake of more environmentally friendly manufacturing methods and of technologies to remove APIs from wastewater streams, and greater focus on so-called green chemistry – creating APIs that are "benign by design" and inherently carry a low ecological risk (Daughton 2014).

There is also a need to more effectively regulate the use and disposal of APIs at the community level. This includes tackling the overuse and overprescription of APIs, and perhaps exploring opportunities for reduced-dose prescribing, and conducting information campaigns to promote wise use through sustainable health-care campaigns. Health agencies that purchase medicines for public use should be made aware of the environmental issues associated with APIs, and discuss these with their suppliers. Waste drug take-back schemes should also be promoted, with better education for customers from prescribers and at the point of sale. Similarly, for veterinary APIs, the risks of overuse and misuse of these products must be effectively communicated to farmers and larger food producers, food retailers and relevant regulatory bodies; appropriate restrictions and support mechanisms can be put in place to limit the impact of veterinary APIs to the intended target species. The use of veterinary APIs to treat diseases in wild populations should also be carefully controlled, and widespread baiting of APIs should be avoided or carefully managed to reduce non-target effects. In addition, while recognizing that the causes of antimicrobial resistance are complex, it is vital that greater effort is made to understand the linkages between veterinary and human use of APIs, environmental exposure, and the development and transfer of antimicrobial resistance genes in pathogens.

It is important also that scientists, practitioners and policy-makers in both the health and biodiversity sciences engage more closely with food producers, pharmacologists, environmental chemists and other relevant stakeholders to better understand and address the potential risks associated with APIs, and assist with identifying cross-cutting indicators – including priority species and ecosystems for future monitoring of potential impacts – to better facilitate cooperation and effective action. This should become an integral part of wider efforts to mainstream a sustainable development agenda into policies and practice in the health-care sector (Vatovec et al. 2013; Schroeder et al. 2013; Morgon 2015). This will become increasingly important in the face of future social and environmental change.

EDWARD N. JOHNSON

11. Traditional medicine

1. Introduction

The contribution of biodiversity and ecosystem services to our health care needs is significant, both for the development of modern pharmaceuticals (Chivian and Bernstein 2008; Newmann and Cragg 2007; see also chapter on contribution of biodiversity to pharmaceuticals in this volume) and for their uses in traditional medicine (WHO 2013). Long before the rise of pharmaceutical development, societies have been drawing on their traditional knowledge, skills and customary practices, using various resources provided to them by nature to prevent, diagnose and treat health problems. Today, these practices continue to inform health-care delivery at the level of local communities in many places around the world (WHO 2013). In socioecological contexts such as these, several resources used for food, cultural and spiritual purposes are also used as medicines (Unnikrishnan and Suneetha 2012). Traditional medicine practices provide more than health care to these communities; they are considered a way of life and are founded on endogenous strengths, including knowledge, skills and capabilities.

Despite noteworthy advances in public health, modern health-care systems worldwide still do not adequately meet the health-care needs of large sections of the population across the globe, and the health and development goals of many communities remain unrealized (Kim et al. 2013; Anonymous 2008). Consequently, health-seeking behaviour in both urban and rural contexts around the world is increasingly becoming pluralistic or a mix of different medical systems. For example, in Peru, the plant knowledge of patients both at herbalist shops and allopathic clinics was largely identical. This indicates that traditional medicinal knowledge is a major part of a people's culture that is being maintained, while patients also embrace the benefits of western medicine (Bussmann 2013; Vandebroek & Balick 2012; Vandebroek 2013). Given the interlinked nature of conservation, health and development, it is relevant to consider community-focused approaches[1] that also address traditional health knowledge and conservation strategies as a way to complement mainstream health systems, and fulfil the basic human right to health and well-being.

1.2 Traditional medicine and biological resources

Biological resources have been used extensively for health care and healing practices throughout history and across cultures. Such knowledge is often specific to particular groups living in distinct

[1] A community here is defined as a group of people sharing a common ecosystem/landscape and associated knowledge.

environments, and is usually passed on over generations (Etkins 1988; 2001; Shankar 1992; Balick and Cox 1996; Vandebroek 2013; see also the chapter on mental health in this volume).

Traditional knowledge in health care can range from home-level understanding of nutrition, management of simple ailments (see also the chapter on nutrition in this volume) or reproductive health practices, to treating serious chronic illnesses or addressing public health requirements. In local communities, health practitioners trained in traditional and non-formal systems of medicine often play an instrumental role in linking health-related knowledge to affordable health-care delivery (e.g. Stephens et al. 2006; Montenegro and Stephens 2006; Reading and Wien 2009). There are also formally recognized practitioners of traditional medical systems, often referred to as complementary and alternative medicine (CAM) practitioners, formally trained in different systems of medicine such as Ayurveda, Traditional Chinese Medicine, Kampo, Siddha, Tibetan medicine, Unani and several others (WHO 2002; WHO 2005, Bodeker et al. 2005; Payyappallimana 2010). Such systems have been institutionalized and integrated into health systems in their respective regions or countries. These have led to the evolution and standardization of local pharmacopoeias that capture the uniqueness of biological diversity and cultural practices of specific socioecological regions, and have specific and well-organized epistemological bases.

Unfortunately, both biological products and health-related traditional knowledge are increasingly threatened (Reyes-García 2010). Overharvesting, land-use change, and climate change are among the major drivers of the decline in wild plant resources, including those used commercially for food and medicinal purposes (Hawkins 2008; FRLHT 1999; 2009; Ford et al. 2010). Analysing the individual and combined impact of these drivers on the biological resources used for food and medicine at different spatial scales is also an important area for further research. Research in the area of medicinal plants and climate change is already emerging (e.g. Zisca et al. 2005, 2008). Although use of faunal resources is not as profuse as that of plant resources, illegal poaching and unwise use of these resources for traditional medicine and hobby pursuits has also taken a toll on the population and diversity of fauna (Milliken and Shaw 2012). Combined, the drivers of change pose a dual threat to wild species and to the livelihoods of collectors, who often belong to the poorest social groups. In this chapter, we highlight the various dimensions related to the conservation of biological resources and promotion of traditional health-care practices, illustrating the relevance of significant areas with case study examples.

2. Trends in demand for biological resources

Plants used in traditional medicine are not only important for local health practices, but also for international trade, based on their broader commercial use and value (Fabricant and Farnsworth 2001). Globally, an estimated 60 000 species are used for their medicinal, nutritional and aromatic properties and, every year, more than 500 000 tonnes (UN Comtrade 2013) of material from such species are traded. A complete list of all plants used in traditional medicine does not exist, but at least 30 000 species of plants with documented use are included in the Global Checklist; an extension of earlier efforts of the World Health Organization (WHO) and Natural Products Alert Database (NAPRALERT) WHO Collaborating Centre at the University of Illinois in Chicago. It is estimated that the value of the global trade in plants used for medicinal purposes may exceed US$ 2.5 billion, and is increasingly driven by industry demand (UN Comtrade 2013).

Fauna and their products are also extensively used in traditional medicine; assessments of the use of fauna and their products are mostly region-, country- or taxa-specific (Alves and Alves 2011; Nunkoo et al. 2012). A variety of animal body parts and secretions are included in traditional medicine pharmacopoeia (Alves and Rosa 2005). Overall, in fact, there is often not a clear line between the consumption for food or medicine, with some species also being consumed for their "tonic" properties.[2]

Increasingly, there is a reverse "re-engineering" or "reverse pharmacology" process being undertaken by researchers, where novel medicines or medical therapies are being developed using traditional processes. Furthermore, institutionalized traditional medicine manufacturers are investing in developing new products that are value additions over existing forms of medicinal formulations (Unnikrishnan and Suneetha 2012).

The demand for herbal medicines is rising drastically, fuelled by factors such as cost–efficacy and higher perceptions of safety. In countries like India, it has been estimated that approximately 80% of medicinal plants are collected from the wild, leading to an increasing pressure on natural resources (FRLHT 1999; 2009). Due to overharvesting and habitat loss, approximately 15 000 species (or 21%) of the global medicinal plant species are now endangered (Schippmann et al. 2006). With rising demand and reducing populations, problems of substitution, adulteration and mistaken identities between species are also on the rise, as illustrated by the example in Box 1.

Box 1. Traditional medicine in a changing world: the example of Peru

The demand for traditional medicine is increasing in Peru, as indicated by the increase in number of herb vendors in recent years, in particular, in the markets of Trujillo. A wide variety of medicinal plants from northern Peru can also be found in the global market. While this trend might help to maintain traditional practices and give recognition to traditional knowledge, it poses a serious threat, as signs of overharvesting of important species are becoming increasingly apparent.

More than two thirds of all species sold in Peruvian markets are claimed to originate from the highlands (*sierra*), above the timberline, which represent areas often heavily used for agriculture and livestock grazing. The overall value of medicinal plants in the markets of northern Peru alone reaches US$ 1.2 million/year. Medicinal plants contribute significantly to the local economy. Such an important market raises questions around the sustainability of this trade, especially because the market analysis does not take into account any informal sales.

Most striking, perhaps, is the fact that seven indigenous and three exotic species, i.e. 2.5% of all species traded, account for more than 40% of the total sales volume. Moreover, 31 native species account for 50% of all sales, while only 16 introduced plants contribute to more than a quarter of all material sold. About one third of this sales volume includes all exotic species traded. None of these species are rare or endangered. However, the rising market demand might lead to increased production of these exotics, which in turn could have negative effects on the local flora (Bussmann et al. 2007b).

A look at the indigenous species traded highlights important conservation threats. *Croton lechleri* (dragon's blood), and *Uncaria tomentosa* (cat's claw) are immensely popular at a local level, and each contributes to about 7% to the overall market value. Both species are also widely traded internationally. The latex of *Croton* is harvested by cutting or debarking the whole tree. *Uncaria* is mostly traded as bark, and again the whole plant is normally debarked. *Croton* is a pioneer species, and apart from *C. lechleri*, a few other species of the genus have found their way into the market. Sustainable production of this genus seems possible, but the process must be closely monitored, and current practice does not appear sustainable because most *Croton* is wild harvested. The trade

[2] http://www.traffic.org/wild-meat/

in cat's claw is so immense that, in fact, years ago collectors of this primary forest liana began to complain about a lack of resources and it was found that often other *Uncaria* species, or even *Acacia* species have appeared in the market as "cat's claw". This is clearly not sustainable.

Some of the other "most important traditional medicinal" species in northern Peru are either common weeds (e.g. *Desmodium molliculum*), or have large populations (e.g. *Equisetum giganteum*). Nevertheless, a number of species are very vulnerable: *Gentianella alborosea, G. bicolor, G. graminea, Geranium ayavacense* and *Laccopetalum giganteum* are all high-altitude species with very limited distribution. Their large-scale collection is clearly unsustainable. In the case of *Laccopetalum*, collectors indicate that finding supplies is becoming increasingly difficult. The fate of a number of species with similar habitat requirements raises comparable concerns. The only species under cultivation at present are exotics, and a few common indigenous species.

There are profound challenges when it comes to the safety of the plants employed, in particular, for applications that require long-term use. Some studies found that various species were often sold under the same common names. Some of the different fresh species are readily identifiable (botanically), but neither the collectors nor the vendors make a direct distinction between species. Often, material is sold in finely powdered form, which makes the morphological identification of the species in the market impossible, and greatly increases the risk for the buyer. The best way to ensure correct identification would be DNA bar-coding. The necessary technical infrastructure is, however, not available locally. The use of DNA bar-coding as a quality control tool to verify species composition of samples on a large scale would require careful sampling of every batch of plant material sold in the market. The volatility of the markets makes this a very difficult task from a logistical standpoint. Furthermore, there is no consistency in the dosage of plants used, and vendors do not agree on the possible side-effects. Even in the case of plant species used for clearly circumscribed applications, patients run a considerable risk when purchasing their remedies in the local markets. Much more control is needed, as well as stringent identification of the material sold in public markets, and those that enter the global supply chain via Internet sales.

While in-situ and ex-situ approaches to conservation are adopted to address the loss of medicinal resources, the success of conservation strategies often depends on the comprehensive involvement of different stakeholders. In this context, the example from India in Box 2 illustrates the potential of in-situ conservation through public–private partnership (PPP) arrangements.

Notwithstanding the inclusion of multiple stakeholders in the implementation of conservation programmes, the sustainability of such initiatives is also dependent on the value of a resource that can be captured by the different actors. It is possible to address some of these concerns through market-based mechanisms such as certification to foster sustainable use standards for medicinal plants, as is being piloted through the FairWild example (Box 3).

Box 2. Conservation and sustainable use of medicinal plants in India

It is estimated that in India, around 300 plants and a few faunal species are in various threat categories and their cultivation is not yet a viable economic option due to the preference for wild sourcing, given lower costs (FRLHT 2009). There is also a general lack of information on agrotechniques (Hamilton 2004).

To address these pressing issues, the Foundation for Revitalisation of Local Health Traditions (FRLHT) in India initiated the establishment of the largest global in-situ conservation network by establishing medicinal plant conservation areas (MPCAs) – as an integrated approach to in-situ and ex-situ conservation programmes. The rationale is to conserve and study medicinal plants in their natural habitats and preserve their gene pool, and to further develop strategies for the management of rare, endangered and vulnerable species. The areas not only provide a good locale for studies on threat assessment, population studies and mapping, but also for participatory forest management, as well as for policy-makers, the community and civil society organizations. Between 1993 and 2014, FRLHT, jointly with the State Forest Departments, established 110 MPCAs across 12 Indian states in a globally unique model of PPP. The programme has been spearheaded in collaboration with the Indian Ministry of Environment and Forests, and through the support of organizations such as the Danish International Development Assistance (DANIDA), United Nations Development Programme (UNDP) and Global Environmental Facility (GEF). Due to its success, the Planning Commission of India recommended the establishment of 200 MPCAs across the country (Tenth Five-Year Plan, 2002).[3] There is also a recent move to recognize these locations as biodiversity heritage sites. A related initiative is the establishment of medicinal plant conservation parks (MPCPs) – a community-based ex-situ conservation initiative aimed at sustainable use of medicinal plant resources and preserving knowledge associated with their use. Coordinated by FRLHT along with other nongovernmental organizations (NGOs) and community-based organizations, a chain of MPCPs has been set up in various parts of India.[4] Attempts have also been made in pilot locations to integrate such medicinal plant-based practices in formal primary health-care centres, apart from promoting them through community health programmes. Within a geographical region, communities have been mobilized to create:

- ethnomedicinal forests and resource centres housing herbaria and crude drug collections;
- local pharmacopoeia databases based on community knowledge;
- community and home herbal gardens and seed banks;
- outreach nurseries for the promotion of cultivation and a sustainable wild collection of medicinal plants;
- trade and enterprise development that aids in income generation.

Moving up the value chain, FRLHT also established a medicinal plant conservation network (MPCN) jointly with a number of NGOs working with different rural communities. As part of this effort, traditional healers' associations have been formed at different levels of administration from the province downwards. The associations conduct regular meetings and exchange of information

[3] See: http://planningcommission.nic.in/plans/planrel/fiveyr/10th/volume2/10th_vol2.pdf

[4] See: http://mpcpdb.frlht.org.

among healers and act according to self-regulatory guidelines, which have been evolved through a participatory process based on the contextual peculiarities of each province. Healers' associations along with NGOs and forest departments have been actively engaged in supporting medicinal plant conservation programmes in various states.

The MPCN is also working on the following issues:

- establishing herbal gardens;
- developing appraisal systems of healers' capacities and training programmes;
- conducting action research interventions in key health areas such as malaria;
- facilitating networking through organizing medical camps, and district- and state-level conventions of healers' associations, but also healer exchange visits within the country and among other Asian and African countries.

Box 3. Sustainable harvest and standards – The FairWild Standard example

The FairWild Standard provides a set of best practice guidelines for the sustainable use and trade of wild harvested medicinal plants. It provides a basis for assessing the harvest and trade of wild plants against various ecological, social and economic requirements. It was developed through a multistakeholder consultation process that has engaged a wide range of organizations and individuals involved with the harvesting and trade of these resources.

Use of the FairWild Standard helps support efforts to ensure that plants are managed, harvested and traded in a way that maintains populations in the wild and benefits rural producers. Version 2.0 of the Standard was developed following the merger of two initiatives: International Standard for Sustainable Wild Collection of Medicinal and Aromatic Plants (ISSC-MAP), which focused on ecological conservation and some social/ethical aspects, and the original FairWild Standard, which focused on social and fair trade aspects. The resulting set of principles and criteria covers eleven key areas of sustainability. It is designed to be an applicable framework in a variety of implementation contexts, as well as to be used as the basis for a third-party certification scheme.

During the development of the FairWild Standard, a number of pilot projects were carried out in locations around the world to test its applicability. These projects included the collection of ingredients used in traditional medicine; for example, the pilots of ISSC-MAP in India under the project "Saving Plants that Save Lives and Livelihoods", supported by the German Federal Ministry for Economic Cooperation and Development (BMZ), and implemented by FRLHT and TRAFFIC India. One of the first studies was conducted in Karnataka, India. Through a participatory planning approach involving various stakeholders such as scientists and community members, a task team was set up for mapping resources and elaborating a sustainable harvesting strategy. As part of the methodology involved documentation of medicinal plant-related knowledge and non-timber forest product (NTFP) collection practices, resource assessments were conducted for selected species. Training was provided for mapping and assessing different harvesting methods. It was found that a well-organized stakeholder group can plan and implement an effective participatory resource management strategy. Apart from standardizing and field-testing the methodology, training modules for wider user groups have been developed. This will be a useful strategy for biodiversity or joint forest management committees through a community-to-community training programme (Unnikrishnan and Suneetha 2012).

Innovation with the FairWild Standard continues in India, with a certification pilot now under way in the Western Ghats. With financial support from the United Kingdom (UK)'s Department for International Development (DfID)/Department for Environment, Food and Rural Affairs (DEFRA) Darwin Initiative and the Keidanren Nature Conservation Foundation, the project intends to increase the capacity of targeted local communities to adapt to climate change and participate in biodiversity conservation through the improved management of socioecological landscapes. It is implemented by the Durrell Institute for Conservation and Ecology (DICE), the Indian NGO Applied Environmental Research Foundation (AERF), UK manufacturer Pukka Herbs Ltd. and TRAFFIC. The project aims to establish supply chains for sustainable harvesting and fair trade in fruit of two tree species used in Ayurvedic medicine (*Terminalia bellirica* and *T. chebula*). A FairWild certification protocol is to be developed for the collection of these species and for establishing a community-regulated mechanism for access and benefit sharing.

The FairWild Standard has also been implemented in other countries of Asia, South America, Africa and Europe (Kathe et al. 2010). In addition to being used by communities for the management of medicinal plant resources, the principles of the FairWild Standard can be used by industry for the development of a sourcing policy to support the development and/or strengthening of national resource management policies and regulations. Of particular relevance to the topic of biodiversity and traditional health is a project that is currently under way as part of the European Union (EU)–China Environmental Governance Programme, which experiments with promoting the adoption of sustainable sourcing according to the FairWild Standard in the traditional Chinese medicine sector, as part of a corporate social responsibility framework. In the international arena, it has also been drawn upon in the development of best practice methodologies for carrying out non-detriment findings (NDF) by the Convention on International Trade in Endangered Speciesof Wild Fauna and Flora (CITES), and as a practical tool for implementing and reporting against the sustainable use objective of the Global Strategy for Plant Conservation (GSPC), as well as the Convention on Biological Diversity (CBD)'s Aichi Targets 4 and 6.

2.1 Socioecological systems

The survival and vitality of knowledge and resources depend on the sociocultural contexts in which they are embedded. Typically, such knowledge and resources are found to be most vibrant among communities (specifically, indigenous and local communities) close to culturally important landscapes. These could relate to socioecological production landscapes (e.g. *satoyama* in Japan) or conservation systems (e.g. sacred groves, ceremonial sites) or therapeutic landscapes (e.g. sacred healing sites). Such landscapes and related traditional knowledge practices make important contributions to health and well-being, therefore necessitating a close inquiry into the functional interlinkages within such systems, and maintenance of their dynamism (Unnikrishnan and Suneetha 2012; Posey et al. 2000; see also the chapter on mental health in this volume). Highlighted below is the case of the Mayan people and their relationship with nature and resources. A sensitive understanding of the cultural ties between societies and nature is required to ensure sustainability of both knowledge and practices.

Box 4. Therapeutic and sacred landscapes

Mayan people maintain a healthy or whole relationship with mother earth and the cosmos through an intricate system of practices and knowledge known as Maya Science (Monterroso & Azurdia Bravo 2008). This divine relationship is enacted by the measure of time using the stars and constellations but also through the use of sacred sites and traditional medicine (Gomez & Caal 2003). The sacred sites (natural and constructed) are places to connect with the ancestors and to contemplate one's role in relation to the social and natural world, but they are also places for healing in the landscape (Gomez et al. 2010). In Guatemala as well as in many other countries, these sacred places are often viewed as a biocultural network that spans land and seascapes, and embody a spiritual dimension of well-being and often underrecognized healing potential (Dobson & Mamyev 2010; Delgado et al. 2010; Verschuuren et al. 2014).

Reyes-García (2010) reviewed the literature on traditional medicine and concluded that the holistic nature of traditional knowledge systems helps to not only understand a plant's efficacy in its cultural context but also improves our understanding of how ethnopharmacological knowledge is distributed in a society, and who benefits from it. In Guatemala, spiritual leaders, midwives, paediatricians, naturopaths, and other traditional healers help counteract the various health problems in communities. To the traditional Mayan healer, the body is composed of the sacred elements; earth, water, fire and air, which correspond to the sun, moon and stars. Therefore, use of traditional medicine is practised based on the date of birth in the sacred Mayan calendar (Monterroso & Bravo 2008).

Within the context of the Mayan calendar, traditional healers know that diseases stem from the spiritual, physical and psychological imbalance of a person, either from wilful violation of proper conduct or due to lack of awareness. Due to colonization and consequent impacts on local and indigenous communities, many traditional practices are fragmented and often combined with elements of western medicine. They are often under ideological pressure and suspicion for the lack a homogeneous theory, while resource scarcity is also an increasing problem underlying the production of many traditional medicines (Delgado & Gomez 2003). Viewing these problems as part of the erosion of cultural knowledge and practices can help in determining suitable and culturally appropriate solutions. For example, Pesek et al. (2009), who researched Maya Q'eqchi' knowledge on medicinal plants and their ecosystems, concluded that traditional ways of protecting plant diversity were better suited to medicinal plant conservation than external conservation solutions based on conservation biology.

Garcia et al. (1999) describe how Mayan medicine in Mexico was reinforced by systematizing the knowledge and experience of 40 traditional healers, and comparing these with other medical traditions, such as Chinese health systems. Striking similarities were encountered, both in concepts as well as practices, such as acupuncture, massage and the use of certain herbs and spiritual healing techniques. This was used to reinforce the local traditional health system, as well as to disseminate the experiences among traditional healers elsewhere in Central America. The exchange of healers' knowledge and practices is generally valued as an invigorating experience that can also provide a platform for the legal recognition of traditional health practitioners (Traditional Health Practioners 2010).

3. Traditional medicine and traditional knowledge at a crossroads

With increasing urbanization and integration of mainstream worldviews, communities often experience alienation from the natural environment (Roe 2010). Cultural systems, including traditional health-care practices, are concomitantly being eroded. As a result, despite the wealth of traditional knowledge that exists, the practice of traditional medicine is declining (Payyappalli 2010). This is further accentuated by institutionalized education systems that often fail to recognize the relevance of these practices, thereby distancing younger generations from exploring such areas (Battiste 2010). The dominant education and research systems tend to emphasize knowledge and technologies with universal standards, rather than supporting the needs of specific regions or populations, and available resources and capabilities (Haverkort et al. 2003). A large part of traditional medical knowledge is experience based and passed on through the oral tradition, and such knowledge is not easily transmitted in classroom-based learning. The institutionalized traditional medical knowledge either gets harmonized with mainstream systems or is not adequately integrated in public health care (Bodeker and Burford 2007), which indicates inefficient use of knowledge and trained human resources.

Access to essential modern health care continues to be a major challenge in many parts of the world. Infectious diseases (such as HIV, malaria, tuberculosis, pneumonia, diarrhoeal diseases and several other neglected conditions), coupled with chronic noncommunicable diseases (such as diabetes and ischaemic heart disease), persistently affect lives in these regions (see also the infectious disease chapter in this volume). Indomitable challenges such as high maternal and child mortality, and emerging and re-emerging diseases (infectious, chronic, and lifestyle-related), are typical constraints to well-being. For these reasons, the role of traditional health-care practitioners in community health is understood as filling a gap in access to modern health care. However, it has to be recognized that in most societies they do play a critical *complementary* role in parallel with the mainstream health system, an aspect that needs to be better appreciated. This calls for a multipronged approach where various resources need to converge, including those related to local health traditions. Experiences over the past two decades show that there is high relevance in aligning biodiversity conservation goals with a community health approach (Miththapala 2006).

The customary absence of comprehensive approaches to assess the role, economic potential and policy implications of traditional knowledge have also been noted as key reasons due to which traditional cultures are frequently disregarded in development programmes, making sustainable development objectives among vulnerable populations more difficult to attain (Jenkins 2000; Haverkort 2003). These issues must all be considered in the context of a global health sector, which predominantly relies on universal models of modern medicine, and continues to be inadequate for large sections of the population around the globe.

New policy forums, such as the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES), are exploring ways of including traditional and mainstream perspectives and methods to undertake an assessment of biodiversity and ecosystem services, and consequent impacts on human well-being. Guidance on the need to understand different kinds of values held by people towards biodiversity and ecosystem services to inform methods of valuation and assessment are being developed, with a specific focus on adequate attention to public health (www.ipbes.net). This calls for stronger partnerships between stakeholders.

A number of leading international NGOs are conducting capacity development activities for traditional health practitioners, such as training, and facilitating networks. One of these NGOs is the Promotion of Traditional Medicines

[5] See: http://www.prometra.org/representations_nationales/uganda.html

(PROMETRA),[5] which has been working to alleviate poor health conditions and services utilizing traditional medicine since 1971. Its unit in Uganda conducts a wide range of capacity development activities for healers, addressing issues such as exposure to potential value addition and income generation activities, culturally sensitive disease prevention and management of environmental conservation. A unique initiative includes training programmes designed for healers and youth from communities on the use of traditional medicinal resources and practices under the banner of Buyijja Forest Schools. PROMETRA also works on integrating traditional medicine in national health systems to improve free choice of medicine for citizens, protect biodiversity and participatory forest management, promote research on medicinal plants, protect traditional knowledge and reinforce institutional capacities of civil society organizations for a healthy environment and sustainable development. Another relevant best practice example is "Friends of Lanka" based in Sri Lanka. It has promoted documentation of practices, and research and networking of traditional health practitioners. For this reason, around 75 healers have been identified among a population of 8000, who treat various conditions such as snake- and insect bites and certain food or natural poisons, which are considered as leading causes of morbidity and mortality in rural areas of developing countries. Friends of Lanka also formed an association of healers, which initiated an assessment of natural resource availability, and methods for conservation and sustainable use through home and community gardens.

Networks such as the MPCN and associations of healers established within its framework are a successful approach to facilitating knowledge and experience exchange among traditional healers nationally, regionally and internationally, resulting in better health and conservation outcomes.

4. Strengthening traditional health practices and addressing loss of resources

To date, there have been several concerted efforts in the international arena to promote both the conservation of biological resources, as well as traditional knowledge. What has been lacking, however, is a comprehensive effort to emphasize the linkages between these elements using an integrated approach that draws on traditional knowledge to complement and supplement modern health-care systems.

With the Earth Summit and adoption of the Convention on Biological Diversity (CBD) at Rio de Janeiro in 1992, significant steps were taken towards political recognition of the relevance of traditional knowledge. In compliance with Article 8 (j) of the Convention, the respect, preservation and maintenance of traditional knowledge, and innovations and practices of indigenous and local communities are related to the recognition of the practices by these communities of their traditional knowledge. Other important aspects of these obligations include promoting the wider application of such knowledge, innovations and practices with the approval and involvement of knowledge holders; and encouraging the equitable sharing of the benefits arising from the use of such knowledge, innovations and practices. These obligations are also applicable to traditional medicine as it relates to traditional knowledge. Furthermore, Article 10 (c) of the CBD states that Parties shall, as far as possible and as appropriate: "Protect and encourage customary use of biological resources in accordance with traditional cultural practices that are compatible with conservation or sustainable use requirements."

Principle 22 of the Rio Declaration on Environment and Development calls for the recognition of, and respect for the knowledge and practices of local and indigenous communities in environmental management towards the achievement of sustainable development.[6] Agenda 21 further specifically calls for an appropriate integration of

[6] The full text of the Rio Declaration is available at: http://www.un.org/documents/ga/conf151/aconf15126–1annex1.htm

traditional knowledge and experience in national health systems, and for conducting research into traditional knowledge related to preventive and curative health practices (Chapter 6 of Social and economic dimensions – protecting and promoting human health) (United Nations 1993). Over the past six decades, two areas where the contemporary relevance of traditional knowledge has been fairly well acknowledged include the management of the environment and natural resources, and the delivery of health care (WHO 2002, 2005, 2013). The need to re-integrate traditional medical approaches into healthcare armamentarium is gaining more political and social acceptance (UN 2010).

4.1 Validation, safety and efficacy of traditional medicine

When a traditional recipe is scientifically validated in terms of safety and effectiveness, and is affordable, available and sustainable, it provides valuable information. It may lead to an officially recommended phytomedicine as well as improvement in the provision of health services to households. In both cases, the aim remains to improve the quality of care in the community.

Integration of modern and traditional treatments is common today. Plural therapeutic itineraries are followed by large numbers of those seeking care. However, this process is often disordered and defined by factors completely extraneous to a rational choice of effective and safe treatment. Scientific and clinical studies may provide essential information to adequately respond to the situation. Research strategies can be based on various methods such as intercultural population studies, historical accounts or biological tests. Beginning with a collection of clinical data during ethnopharmacological field studies may be a good start.

Many users of traditional medicines and practitioners claim that the effect of a treatment is obvious when there is an improvement in the health status.[7] However, most ailments tend to get better over time even without any care. In clinical studies (with human subjects), observations are organized in a way that makes it possible to know whether observed outcomes can be attributed to a given treatment. This can be obtained through a dose-escalating prospective study (comparing outcomes with different doses of a treatment), or with the leading benchmark of medical research and evidence-based medicine: a randomized controlled trial.

Before doing so, it is relevant to determine which is the best among the various treatments used to treat the same ailment in a population. The "bedside-to-bench" approach has been used with some success to answer this question; it is based on precise clinical information on real cases and statistical analysis of correlations between treatments and outcomes (Willcox et al. 2011). The clinical effects of medicinal plants should be studied using sound methods that are, insofar as possible, the same as or compatible with methods used for testing conventional medicines. This could produce results that are understandable and more widely acceptable to the scientific community, health professionals and policy-makers. It can also provide information useful for the quality of care in the community. However, it is also important to acknowledge that traditional formulations might sometimes require testing within traditional epistemologies and methods, to avoid the potential misrepresentation of effectiveness due to incommensurability of methods (Shankar et al. 2007). The examples in Boxes 5, 6 and 7 illustrate examples of good practices in Palau, Mali and India to validate and revitalize traditional medicinal practices, mindful of the safety, quality and efficacy of the practices, and an inclusive approach with practitioners of traditional medicine.

[7] This observation is based on field work conducted by the authors of this chapter.

Box 5: Participatory approaches to validation: experiences from Palau and Mali

A relevant example linking traditional medicines and noncommunicable diseases (NCDs) is the survey performed in Palau on traditional medicines (or health practices) and NCDs – chiefly diabetes and high blood pressure. A nationwide survey was carried out to determine which traditional medicines are most commonly used to treat these conditions, and what was the perceived effectiveness. Data were collected as part of a training course on scientific research. A distinctive feature of the results obtained was that, among 30 plants used for diabetes, two were the most common (Table 1). [8]

Table 1: Ingredients of traditional treatments most commonly used for diabetes

(mentioned ≥4 times, among 45 respondents with diabetes) in Palau (unpublished, 2014)

Name of the plant	Palauan name	No. of reported uses	N (%) reported "lower sugar level in blood"
Phaleria nisidai	delal a kar	13	6 (46%)
Vitex trifolia	kelsechedui	4	1 (25%)
Scaevola taccada	korai (kirrai)	4	1 (25%)
Morinda citrifolia	ngel/noni	12	0 (0%)
Phyllanthus palauensis	ukelel a chedib	4	1 (25%)

The difference between the reported outcomes with the two most commonly used plants was statistically tested. When comparing reported outcomes of *P. nisidai* and *M. citrifolia*, *P. nisidai* was statistically more often associated with the reported outcome "lower blood sugar" (P=0.01). None of the patients using *M. citrifolia* reported the outcome "lower blood sugar", even though this plant was the second most frequently used.

Following the identification of *P. nisidai* through this brief survey, a literature search was performed to identify a potential link between the results obtained and what is known about the antidiabetic properties of the plant. It was found that the high mangiferin content of *P. nisidai* could explain the observed effects. Indeed, in vitro and animal studies on this substance showed improvement in the glucose tolerance test, inhibition of alpha amylase, alpha glucosidase and dipeptidyl peptidase IV (as with some of the most recent antidiabetic drugs), increased insulin secretion and a hypolipidaemic effect (Kitalong 2012).

In a study on traditional treatments for malaria in Mali, use of the retrospective treatment outcome (RTO) method resulted in a database of treatments taken for malaria cases in 952 households. From the 66 plants used, alone or in various combinations, one was clearly associated with the best outcomes: a decoction of *Argemone mexicana* (Table 2) (Diallo et al. 2007).

[8] For a review of herbal medicines used to treat diabetes, see also Rao et al. 2010.

Table 2: Correlation between plants used and reported outcome in a study on traditional treatments for malaria in Mali

Plant	Total number of people used on	Healed	Failed	% Healed (95% CI)	*P* (Fisher exact)
Argemone mexicana	30	30	0	100% (88–100)	Reference
Carica papaya	33	28	5	85% (68–95)	0.05
Anogeissus leiocarpus	33	27	6	82% (64–93)	0.03

The recipe that showed the best outcomes in patients, a single plant in its traditional mode of preparation and utilization, was selected for a further dose-escalating observational study, followed by a randomized, prospective, comparative clinical trial (randomized controlled trial with the selected local remedy versus the standard, imported treatment). After these clinical studies, the search for active compounds was undertaken. The whole research process was labelled "reverse pharmacology" or, more specifically, "bedside-to-bench" approach.

Box 6: Traditional antimalarials – RITAM experience

There are a number of successful models and programmes for preventive and curative health interventions that use traditional medicine and practices to achieve the desired goals. In the field of malaria treatment, there is the Research Initiative on Traditional Antimalarial Methods (RITAM), which was initiated in 2001 (Willcox et al. 2003; Willcox & Bodeker 2004 www.gifts-ritam.org). This initiative is based on a group of international researchers exploring ways to increase the relevance of including traditional medicine in the repertoire of choices available for the prevention and cure of malaria. As such, RITAM is working on traditional antimalarials with more than 200 members from over 30 countries. A systematic literature review by RITAM indicates that numerous plant species are used to treat malaria or fever. In India, FRLHT has been assessing the effectiveness of traditional medicine for malaria prevention through a participatory community-based approach. This includes conducting a literature survey on plant drugs used for malaria management, as well as documenting traditional antimalarial remedies and dietary rules for malaria prevention. Finally, pharmacological references of the toxicology and efficacy of these practices from Ayurvedic and modern medical literature are compiled. As part of FRLHT's malaria prophylaxis approach, communities in selected endemic areas follow a regimen of malaria prevention (mainly consisting of an herbal decoction) during the monsoon season for a selected period. The safety of the practice is assured and the remedy is prepared fresh on specific days at a community centre. By using a cohort study approach, groups based in several regions that do not follow this regimen are compared with those that do. Data gathered in the documentation has shown positive results for malaria prevention, indicated by statistically significant positive outcomes.

The case of the RITAM initiative (in Box 6) highlights that utilizing traditional medical knowledge through community-based participatory approaches is feasible and urgently needed to find solutions to the continuing high incidence of preventable and curable diseases such as malaria in regions where it is endemic. This also requires the consideration of ethical factors, e.g. free, prior and informed consent (Unnikrishnan and Prakash 2007). Home herbal gardens is a successful model to promote access to health care through sustainable natural resource management of medicinal plants.[9] According to observations, it has successfully reduced poverty in rural areas and revived local knowledge of medicinal plants and traditional health practices. Today, 200 000 home gardens across 10 states in India are used to meet the primary health-care needs of some of the poorest households, while reducing their health expenditure. A majority of participants are now contributing fully to meet the costs of raising their medicinal plants. Some studies show that there is substantial health cost saving due to the use of home remedies (e.g. Hariramamurthi et al. 2006; Bode and Hariramamurthi 2015).

5. Challenges to the protection of traditional medical knowledge

Many pharmaceutical drugs used today have been derived from plants that were initially used in traditional systems of medicine (Fabricant and Farnsworth 2001). According to WHO, approximately 25% of these are plant derived.[10] Health-related traditional knowledge has been commonly accessed for developing new medicines, although knowledge, practices and resources have often been misappropriated (Timmermans 2003). The extent to which traditional medicine can guide drug discovery has been subject to controversy, contributing to fluctuations in investment in bioprospecting informed by ethnobotanical data (Saslis-Lagoudakis 2012).

5.1 Databases for health-related traditional knowledge

Searchable databases for health-related traditional knowledge, which ensure the protection of related resources and knowledge, are currently being developed. A unique database project is the Traditional Knowledge Digital Library, which was developed through collaboration between the Council for Scientific and Industrial Research, the Indian Ministry of Science and Technology, and the Ministry of Health and Family Welfare (Department of AYUSH). An interdisciplinary team of experts from Ayurveda, Uniani, Siddha and Yoga as well as from information technology (IT), law and scientists manages the digital library. It involves documentation of the traditional knowledge available in the public domain in the form of existing literature related to Ayurveda,

Box 7: Home herbal gardens as a self-reliant community health programme

A self-reliant approach to managing simple, common health conditions can reduce the health expenditure of poor rural households and rural indebtedness in many developing countries (Van Damme et al. 2003). Home herbal gardens, as conceived by the FRLHT, are a collection of 15–20 prioritized medicinal and nutritional plants, and have become a successful model for a self-reliant community health programme. Apart from being a conservation milieu for medicinal plants, it also addresses nutritional challenges. In most rural communities, knowledgeable women take care of certain primary health needs of the family members and the gardens become a handy resource for them. Some women, by taking on the role of suppliers of seedlings for the programme, also earn supplementary incomes.

[9] For other health benefits of home gardens, see also the nutrition chapter in this volume.

[10] http://www.who.int/mediacentre/factsheets/fs134

Unani, Siddha and Yoga, in digitized format in five international languages: English, German, French, Japanese and Spanish. Furthermore, for the purpose of systematic arrangement, dissemination and retrieval, the Traditional Knowledge Resource Classification, an innovative structured classification system, has been developed for about 25 000 subgroups related to medicinal plants, minerals, animal resources, their therapeutic uses, clinical applications, methods of preparation, modes of administration, etc.

By providing information on traditional knowledge existing in the country, in languages and formats comprehensible to patent examiners at international patent offices, the database contributes significantly to preventing the grant of wrong patents. In parallel, various organizations are undertaking a similar exercise to document oral knowledge or knowledge in the informal domains through the development of community knowledge registers. Chiefly led by NGOs, these registers attempt to rally community members to discuss and document their knowledge and practices in different categories of resource use or practices based on two premises: (1) that by documentation, they establish prior art over the knowledge and resource use, and (2) it promotes greater use and practice of the knowledge within the community, eventually reinforcing such use as strong social traditions.

Community biodiversity registers have been developed and promoted as *sui generis* documentation systems to protect biodiversity-related traditional knowledge (Gadgil et al. 2000). These have been incorporated in the national laws of various countries. In India, for example, these registers have been further executed through biodiversity management committees (the lowest level of governance unit) that are engaged in systematic documentation of local resources and knowledge. More recently, communities have been articulating their rights over their knowledge and resources by developing their own biocultural community protocols. Defined by communities, these highlight the legal rights that are vested in communities by virtue of international and national laws, and provide a self-description of the community profile, their resources, rights and responsibilities. They also provide an indication of the terms of engagement with external agents. These documents therefore can be viewed as legal tools to foster protection of the rights of communities.

These databases are useful for exemplifying the value of encouraging the development and improvement of community knowledge registers and biocultural protocols, and linking them with national databases for protection. They also show that it is necessary to build on and scale up good practices of ethical and equitable agreements with international collections and industries related to the use of traditional knowledge and natural resources for research or commercial purposes. Moreover, despite all their inherent challenges, web-based databases can also be an important tool for the exchange of information between ethnopharmacological studies and the public, and for the dissemination of information between researchers, planners and other users (Ningthoujam et al. 2012).

More recent trends show a process of "reverse engineering", where traditional processes and methods are deployed for the development of mainstream novel products. This again raises questions of the commensurability of attributions to existing knowledge with the novelty definitions of intellectual property laws.

As most of the traditional environmental and medical knowledge among communities is oral in nature, revival of the social processes of their generation, preservation and transfer within communities needs to be well studied, despite all the inherent challenges associated with this. Furthermore, traditional medical knowledge can inspire industrial research and development processes in bioresource-based sectors, which require mechanisms to secure appropriate attribution and sharing of rights and benefits with knowledge holders, as set out in the text of the CBD and the Nagoya Protocol on Access to genetic resources and equitable sharing of benefits arising from their commercial utilization.[11] The example in Box 8 illustrates an initiative that attempts to integrate these issues while raising the capacities of multiple stakeholders in achieving better public health outcomes in Africa.

Box 8: Capacity building on plant research for better public health in Africa

The Bamako Global Ministerial Forum on Research for Health organized by WHO was held in November 2008 to strengthen research for health, development and equity. The Bamako call to action notably prioritized the development of policies for research and innovation in health, especially related to primary health care and the strengthening of research capacity by building a critical mass of young researchers (WHO 2008). It was this call to action that led to the creation of the Multidisciplinary University Traditional Health Initiative (MUTHI): Building Sustainable Research Capacity on Plants for Better Public Health in Africa, initiated in January 2010 and set to be finalized in December 2014.

The MUTHI project was established with European Union funding (Framework 7 Programme) to build more sustainable plant research capacity and research networks between key institutions in Africa (Mali, South Africa and Uganda) and a group of partner research institutions in Europe (Norway, UK and the Netherlands) to attain better health in Africa (MUTHI 2013). The project has provided a four-year capacity-building programme, in which African researchers are trained in all the necessary skills to produce and commercialize safe and standardized improved traditional medicines (ITM), and are trained in intellectual property rights (IPR) regulations and principles of access and benefit-sharing (ABS). The project is based on the needs of the African partner institutes to strengthen their ethnopharmacological research capacities in the area of ITM.

For more effectiveness, the MUTHI project has been divided into work packages that each focus on a different aspect of the project: (1) training in medical anthropological and ethnopharmacological research skills to conduct high-quality ethnobotanical and ethnopharmacological research on medicinal plants; (2) quality control of phytomedicines and nutraceuticals; (3) investigative bioactivity and safety of phytomedicines and nutraceuticals, with the objectives of assessing the needs of African institutes and developing the capabilities of researchers for bioassays, data management, quality assurance, bioactivity evaluation, safety aspects and developing guidelines; (4) identify researchers' needs for clinical and public health training, and build the capacity of traditional medicine researchers on all aspects of the subject, including writing and data analysis; (5) examine ethics and IPR, aiming to assess training and education requirements for stakeholders on IPR, biodiversity legislation and regulation, ABS, and ethics of traditional medicine and research methods (Bodeker et al. 2014, Bodeker et al. 2015). A sixth work package is charged with project management.

The benchmark referenced in the MUTHI project is the Code of Ethics of the International Society of Ethnobiology (ISE), initiated in 1996 and completed in 2006. Contrary to other frameworks, the ISE Code of Ethics addresses the rights of the individual knowledge holders. Participants of the first work package conducting an ethnobotanical and retrospective treatment outcome study have been trained through workshops focused on research skills, ethics and IPR, and have received online guidance in writing their research proposals, including a section on research ethics and free prior informed consent (FPIC). The latter had to be established at individual and collective levels,

[11] The Nagoya Protocol on Access to genetic resources and equitable sharing of benefits arising from their commercial utilization (Nagoya Protocol), adopted by the Tenth Conference of Parties to the CBD, was concluded on 29 October 2010 in Nagoya, Japan. It provides the framework to facilitate access and benefit sharing. See http://www.cbd. int/nagoya/outcomes/

as determined by community governance structures before the start of the research. The affected communities were provided with complete, comprehensive information regarding the purpose and nature of the proposed programme, project, study or activities, the probable results and implications, including all reasonably foreseeable benefits and risks of harm (be they tangible or intangible) to affected communities. The work package team that is responsible for all aspects related to IPR and ABS within the MUTHI project provided a needs assessment followed by workshops on ethics and IPR, and mentored participants from all of the partner countries in developing memoranda of understanding between researchers and traditional healers, including aspects related to FPIC and ABS. The drafting phase of the memoranda of understanding was an ongoing process between the researchers and traditional healers in order to reach a final memorandum of understanding approved by all stakeholders (Bodeker et al. 2015).

6. Ways forward

Despite the multiplicity of policies, goals and targets to address health, environment and development challenges, we are still far from achieving the stated objectives of policy forums, chiefly because of a lack of synergy and integration in policy implementation. Moreover, mainstream health sector practices often continue to neglect broader determinants of health or intersectoral linkages to health. There is increasing recognition from the academic community and public alike that no single system of knowledge can solve the mounting problems of humanity (Rai et al. 2010; Bodeker and Burford 2007), and a more comprehensive multidisciplinary and pluralistic strategy is needed.

One possible way forward to address the interconnected issues of conservation (of knowledge and biological resources), and equitable and affordable health-care provision is to undertake an integrated approach with the full involvement of communities. However, there is no universal way to achieve this goal and no homogeneous methodology that can be applied (Wage et al. 2010). Traditional knowledge on health and biological resources is by its very nature context specific. Culturally sensitive and locally appropriate approaches are required (see also the chapter on mental health in this volume).

Some multipartner initiatives, such as the Biodiversity and Community Health (BaCH) Initiative, attempt to pool the individual strengths of different agencies to synergize multiple efforts to achieve biodiversity conservation, and health and development, especially at the local levels of implementation. Launched as a global multistakeholder initiative in 2012 during the eleventh Conference of the Parties to the CBD in Hyderabad, India, it primarily aims to develop and mainstream community health approaches by supporting traditional knowledge and biodiversity conservation, and promoting the sustainable use of biological resources by building on lessons learned. It also aims to exchange knowledge with partners from both the government and nongovernment sectors, as well as international organizations.

The Initiative underscores the role of the ecosystem as a reliable and low-cost service provider, and supports sustainable natural resource management. It also revitalizes effective traditional medical knowledge and local remedies by developing knowledge, skills and capabilities of the populations living in close proximity to biological resources. Under the coordination of the United Nations University Institute for the Advanced Studies of Sustainability (UNU-IAS), the BaCH is simultaneously addressing the following objectives: (i) the integration of conservation priorities in health system planning; (ii) raising the contemporary relevance of traditional medicinal practices; (iii) identifying and piloting best practices for local innovations through livelihood programmes and for self-reliant health systems; and (iv) operationalizing a comprehensive health and well-being approach by working with relevant stakeholders and actors.

6.1 Innovations and incentives

It is important to leverage and strengthen the high patronage for traditional medical care to improve public health outcomes and achieve the reemerging broader objectives of "Health for All" (WHO 1998) and "Good Health at Low Cost" (Balabanova et al. 2013). This requires enabling decentralized approaches that allow better access to health care, are culturally sensitive and contribute to more comprehensive knowledge on the use of biological resources and health.

Implicit to decentralized conservation measures is the need to strengthen local innovation. This may be achieved through awards, assistance for livelihood programmes based on medicinal resources and local enterprises, appropriate intellectual property protection, and relevant cross-sectoral collaboration at all levels. It is further relevant to develop the capacities of traditional health practitioners to provide safe and effective health care, and build sustainable partnerships with different collaborators (Brewer 2014). Mechanisms for the protection of such traditional knowledge resources, prevention of their erosion and linking them with scientific research are related areas that also need further attention.

The value chains of traditional medicine and, generally, medicinal resources are often linked to various sectors, with much of the primary supplies provided by local communities reliant on the same ecosystems and life-supporting services they provide. Harnessing their knowledge on the identity and use of medicinal resources, and their sustainability can be strengthened by improving the economic returns from their efforts by promoting value-added activities at the local level. Encouraging the development of enterprises based on medicinal and nutritional resources and services, and of new, appropriate and feasible technologies that could enhance productivity and quality of resources would further complement conservation measures, as they serve as economic and social incentives. Examples of innovative strategies and initiatives linking conservation and community health are described in Boxes 9 and 10.

Box 9. Community livelihoods – linking conservation with community health

There are several successful cases that highlight how the sustainable management of medicinal plants can impact community livelihoods, leading to income generation and improved community health (see, for example, Hamilton 2004; Hamilton & Hamilton 2006).

One such initiative is the Muliru Farmers Conservation Group, a community-based organization located near Kakamega forest in western Kenya. The group generates income through the commercial cultivation and secondary processing of an indigenous medicinal plant, *Ocimum kilimandscharicum* to produce the Naturub® brand of medicinal products.

The enterprise reduces pressure on the biodiverse Kakamega forest by offering an alternative to the exploitation of forest resources, while the commercialization of the medicinal plant has heightened local appreciation of the value of the forest's biodiversity. Over half of the project participants are women and 40% of participants rely entirely on this initiative for their income. The enterprise invests a portion of its revenues in forest conservation and biodiversity.

Since the processing facility opened, over 770 tons of community cultivated *O. kilimandscharicum* leaves have been processed. Over 400 000 units of Naturub® products have been sold in both urban and rural areas of Kenya. The products have received wide acceptance in the market. The total revenue from the project thus far has been over US$ 70 000. Currently, over 360 rural households cultivate the plant on smallholder farms.

Box 10. Herbanisation: an open-access, medicinal street garden project for greening, healing and connecting in Cape Town, South Africa

Cape Town, South Africa is home to a vast trade in medicinal plants, with 262 tonnes of wild medicine being harvested from within the city annually (Petersen et al. 2014a; Reid 2014). The illicit harvest of plant material from the city's protected areas, prompted by local demand and the economic marginalization of many healers, has brought herbalists and conservation authorities into conflict. The intersection of conservation priorities, livelihoods based on wild-harvested plants, and health and well-being has resulted in a conservation conundrum (Petersen 2014b). It was in light of this conundrum that the Sustainable Livelihoods Foundation, a nongovernmental organization based in Cape Town, collaborated with Rasta bushdoctor (herbalist) partners to establish "Herbanisation".

Herbanisation is an open-access, medicinal street garden project based in Cape Town. The project aims to green degraded streetscapes in economically marginalized areas while contributing to the livelihoods of local Rasta and Khoi herbalists, and reconnecting community members with medicinal plants and indigenous knowledge. Herbanisation began as a pilot project of 250 medicinal plants in 2012. Originating in Seawinds, an area of high unemployment and many social ills such as gangsterism, drug abuse and violence, the garden was established on a pavement beside an existing community nursery, with open access to local healers and the community. The project wanted to connect, heal and green the community through plants. Since the inception of the pilot project in 2012, Herbanisation has expanded to include approximately 1700 plants in Seawinds, Cape Town, and is set to reach 4500 by mid-2015.

Herbanisation has already resulted in groundbreaking engagement between Rasta herbalists, conservation bodies and local botanical organizations. In addition, the project is strengthening linkages between park activities and urban conservation efforts, making local nature a key driver of urban renewal efforts. In terms of the impact on the local neighbourhood, many Seawinds residents and local traditional healers harvest from the Herbanisation street gardens in order to treat themselves and their families. Not only does this contribute to the health and well-being of the local community, but it also empowers individuals to take their health into their own hands and feel proud of their role as indigenous knowledge bearers.

Three guiding principles have been key to the success of the project to date. First, work with local champions: our project was born out of a partnership with Neville van Schalkwyk, an accomplished gardener and Rasta herbalist elder in Seawinds. Working with established, respected and dependable individuals is key to project longevity and success. Second, use gardens as vehicles: while providing herbalists and the community access to medicinal plants is a key aspect of the project, the gardens also serve as places and processes through which conversation is enabled between herbalists, conservation authorities and the government. This is vital in linking grass-roots community efforts with regional policy design and implementation. Third, apply open-access principles: we have chosen to establish gardens on disused public open spaces where plants are freely accessible to the local people. This model encourages interaction between people and plants, while stimulating knowledge exchange and fostering a sense of community participation and ownership.

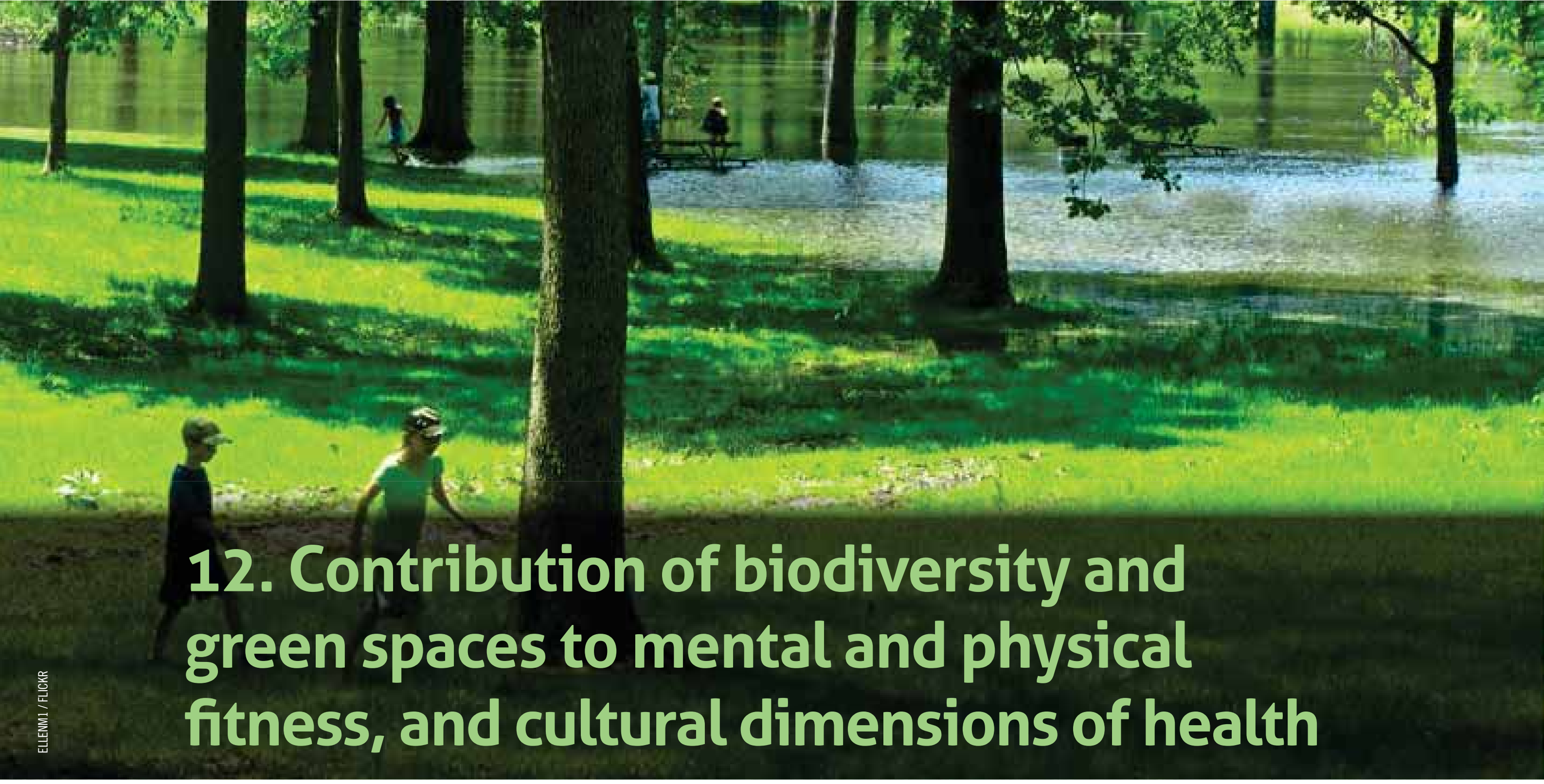
These cases highlight that promoting enterprises through traditional medicinal resources and products – where stakeholders in close proximity to biological resources and knowledgeable about their use also gain a fair share from the value chain – are successful models that can address both improved livelihoods and sustainable natural resource management.

6.2 Capacity and research needs and development approaches

Sustainable medicinal resource management for both captive breeding and wild collection is important for the future of traditional medicine. It should involve all stakeholders, including conservationists, private health-care sector, medical practitioners and consumers. It is important to increase partnerships at the local, national, regional and global levels by supporting/facilitating enhanced networking among various stakeholders, such as in value chain partnerships, and learning partnerships among and between peer groups. Good examples include the development of standards and certification schemes, such as the FairWild Standard developed by TRAFFIC, International Union for Conservation of Nature (IUCN), World Wildlife Fund (WWF) and other partners in a multistakeholder, inclusive consultation process as a best practice tool to verify that the wild collection of plants is ecologically sustainable and trade is equitable. A complementary initiative is the BioTrade Verification Framework for Native Natural Ingredients developed by the Union for Ethical BioTrade. These efforts enable monitoring of collection and trade practices, and tracing the movement of resources, in addition to fostering sustainable use practices that allow benefits to different actors in the supply chain. Furthermore, such partnerships could potentially enable the facilitation of financial support mechanisms to promote research and development, capacity development and awareness activities related to traditional medical knowledge.

Traditional approaches to health care have been tested empirically, albeit without adequate documentation. Documenting such experiences and thereby fostering a participatory learning process to identify and supplement current practices in a culturally sensitive way is a significant challenge. As seen from the examples from Palau, Mali and India, there is also value to be gained from reflexive methods of capacity development, which foster learning between experts external and internal to the traditional medical systems, at various levels of operation, including the sustainable use and protection of the resources.

Further research is also needed to assess the individual and combined impact of drivers of change at the local, national and global scales, which lead to the loss of species used for food, traditional medicines or as the basis for pharmacological compounds. Unsustainable harvest, land-use change, urbanization, illegal trade and climate change are among the key drivers that have already hindered access to and the potential long-term viability of these resources. It is important to examine the response of medicinal plants and other pharmacological compounds to climatic changes. Interdisciplinary research in this area can provide valuable insights to public health and conservation scientists, policy-makers and local communities, who depend on them for their health, livelihood and well-being.



12. Contribution of biodiversity and green spaces to mental and physical fitness, and cultural dimensions of health

1. Introduction

Examining the interlinkages between biodiversity, mental health and health in all its dimensions as defined by the World Health Organization (WHO) ("a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity") demands that we explore the interrelationships among biological and cultural diversity, and between physical and mental health, to foreground integrative and interdisciplinary approaches and research that draws from different disciplines, and that we are able to accommodate diverse perspectives. Integrative approaches that explicitly engage with biodiversity, physical and mental health, along with cultural and ecosystem dynamics, continue to emerge in fields such as ecosystem approaches to health, Ecohealth and One Health, with a growing focus on interrelationships among the health of humans, animals and other species in the context of social–ecological systems (see, for example, Charron 2012; Waltner-Toews 2004; Webb et al. 2010; Wilcox et al. 2012). At the same time, scientific and clinical studies drawing from other fields such as immunology can contribute invaluable insights into these multifaceted dimensions. The connections between biodiversity, mental health and physical activity are particularly relevant in the context of a shifting global burden of disease, in which noncommunicable diseases (NCDs) are the most rapidly rising challenge to global public health.

As discussed in the sections that follow, contact with nature may not only be associated with positive mental health benefits, but can also promote physical activity and contribute to overall well-being. Biodiversity can have both direct and indirect benefits for physical and mental health (Pretty et al. 2011), just as it can sometimes pose direct and indirect health threats, particularly when unsustainably managed or compounded by global threats such as climate change.

Other indirect benefits, not traditionally considered in the global public health agenda, include the contribution of biodiversity to the provision and sustenance of a range of cultural ecosystem services such as spiritual values, traditional food cultures, educational values and social relations.[1] If our cultural perspective assumes that "biodiversity" refers to "all life forms" then as humans we are inseparable, and

[1] From the Agenda 21 for Culture: cultural diversity is defined as "a means to achieve a more satisfactory intellectual, emotional, moral and spiritual existence." (Agenda 21 for Culture 2004). Based on this view, the starting proposition, that there are linkages between biodiversity and human health, is more adequately framed by examining the diversity of life *in toto*, rather than separate nature from culture.

we interact with other life forms in a myriad of ways that is life itself; indeed, without life forms there would be no life on the planet, including our own. A different cultural perspective might see the interlinkages between biodiversity and health as important to explore because of a perceived loss of biodiversity, and the environmental degradation that has arisen as part of modern industrial societies, rapid population growth and the urban/agricultural settings of the contemporary anthropocene.[2]

Accordingly, this chapter examines the interlinkages between biodiversity and mental health, including with consideration for its social and cultural dimensions and the way these components of human health and well-being also relate to cultural ecosystem services. In light of the relationship between physical inactivity and NCDs, this chapter also examines the potential links between biodiversity and physical fitness, including in urban settings. As biodiversity is also central to cultures, cultural traditions and overall well-being, building on the findings of the chapters on traditional medicine and nutrition in this volume, this often-neglected dimension of health will be discussed in the fourth section of this chapter.

2. Biodiversity and mental health

Mental health is defined by WHO as "a state of well-being in which every individual realizes his or her own abilities, can cope with the normal stresses of life, can work productively and fruitfully, and is able to make a contribution to her or his community" (WHO 2001). In addition to an increase in the incidence of NCDs such as as heart disease, chronic obstructive pulmonary disease, stroke and cancer, mental disorders contribute to a significant proportion of the global disease burden (Beaglehole and Bonita 2008; Beaglehole et al. 2011). Depression alone accounts for 4.3% of the global burden of disease and is among the largest single causes of disability worldwide, particularly for women (WHO 2013). Between 1990 and 2010 alone, major depressive disorders increased by 37% (Murray et al. 2012).

People with schizophrenia and psychosis suffer from poorer physical health and die on average 15–20 years earlier than the general population (Schizophrenia Commission 2012). This is aggravated by sedentary lifestyles, poor diets, smoking and weight gain from antipsychotic medications and antidepressants, in turn associated with an increased risk of obesity, cardiovascular disease and diabetes (Schizophrenia Commission 2012).

Promoting physical activity in people and knowing more about *where* people with mental health problems should recreate could, therefore, be more of a public health priority. Little is known about the types of environments that can best support physical activity in this population or what types of environment alleviate – or aggravate – psychotic symptoms.

Green spaces in urban settings are linked to stress reduction (Roe et al. 2013; Aspinall et al. 2013; Ward Thompson et al. 2012), neighbourhood social cohesion (Maas et al. 2009), reductions in crime and violence (Branas et al. 2011; Kuo and Sullivan 2001; Garvin et al. 2013), and a range of other health benefits associated with psychological, cognitive and physiological health (see Box 1; for recent reviews, see Sandifer et al. 2015; Logan 2015 and Rook et al. 2013). Green space and tree canopy percentage have also been found to have a strong inverse correlation with objective measures of depression, anxiety and stress (Beyer et al. 2014)

There is strong evidence for the benefits of interaction with nature – including domestic animals, and wild animals in wild settings – in treatments for depression, anxiety and behavioural problems, particularly in children and teenagers (e.g. Kuo and Taylor 2004; Markevych et al. 2014; Wells 2014; Roe and Aspinall 2011a). It has been argued that contact with nature is important for

[2] Pretty et al. (2008) embraced these different perspectives in the following way: "There is a common recognition around the world that the diversity of life involves both the living forms (biological diversity) and the world views and cosmologies of what life means (cultural diversity)."

childhood development, and children who grow up with knowledge about the natural world and the importance of conservation may be more likely to conserve nature themselves as adults (Kahn Jr & Kellert 2002; Taylor et al. 2006). Conversely, a growing number of studies have suggested that children, particularly in developed countries, increasingly suffer from a "nature-deficit disorder",[3] due to a reduction in the time spent playing outdoors, potentially a result of increased use of technology, and parental and societal fears for child safety (Mustapa et al. 2015; Derr and Lance 2012; McCurdy et al. 2010; Godbey 2009).[4]

Nature connectedness refers to the degree to which individuals include nature as part of their identity through a sense of oneness between themselves and the natural world (Dutcher et al. 2007; Schultz 2002). Beyond an evolutionary affiliation to other life on earth, the hypothesis here is that a sense of connection between one's self and biodiversity is also critical for mental, social, physical and cultural health. Re-developing this connection has been described as a series of steps involving the acquisition of knowledge (information about nature), developing an understanding based on physical experiences in nature, and moving towards being connected and committed (Zylstra 2014).

People with high nature connectedness tend to have frequent, long-term contact with nature and spend the most time outdoors (Chawla 1999), exhibit ecologically aware attitudes and behaviours (Nisbet et al. 2009; Parks Canada, 2011; Wellman et al. 1982; Williams & Huffman, 1986), and are happier (Zelenski & Nisbet, 2014). These characteristics translate to being more supportive of conservation and predict greater likelihood to express environmental concern (Dutcher et al. 2007; Mayer and Frantz 2004).

Recent studies have shown that it is not only the availability and quantity of greenery that matters, but also the quality and depth of the green spaces, in terms of species richness and heterogeneity (e.g. Werner and Zahner 2010; Sandifer et al. 2015). Measurable positive associations between species richness, including microbial diversity, and aspects of psychological well-being have been demonstrated, suggesting that habitat heterogeneity could be a cue to the perceptions of, and positive outcomes from, biodiversity (Shwartz et al. 2014). Hence, the design and management of green spaces in urban environments should take biological complexity into consideration for the enhancement of human well-being, on top of the usual considerations of biodiversity conservation that focuses on restoring the biotic integrity of ecosystems themselves. Aspects of biological complexity include species composition, functional organization, relative abundance and species numbers. These notions have been used for hospital design (see Box 2).

As discussed in the chapters on microbial diversity and nutrition in this volume, there is a growing body of scientific evidence that demonstrates the importance of (non-pathogenic) microbial inputs from the environment and dietary patterns in determining public health outcomes. An increasing proportion of this emerging research specifically examines the relationship between the human microbiota, exposure to microbial biodiversity through the natural and built environments, and diets, with corresponding implications for NCDs, including depression and anxiety (e.g. for a recent review, see Logan 2015 and Rook 2013 and references therein). Importantly, these studies also consider how socioeconomic and environmental factors may modulate and mediate health outcomes (see also section 3 in this chapter). These findings are also useful to inform the design of urban landscapes that jointly promote the mental

[3] A term coined by journalist Richard Louv in 2005

[4] Some research has suggested that some children, particularly those from urban areas, are fearful of spending time in certain natural habitats (woodland and wetland) owing to perceived threats from isolation, wild animals or the actions of other people (Bixler & Floyd 1997). The biophilia hypothesis asserts that humans have an evolutionary affiliation to nature (Wilson 1984). Although those with strong traditional or local ecological knowledge bonds are more likely to have maintained strong connections to the natural world, today more than half of the world's population lives in cities, often reducing contact with biodiversity to infrequent time spent in green spaces and visits to parks. Consequently, Western cultures are increasingly concerned about the growing disconnect between humans and nature (Dallimer et al. 2012; Louv 2008).

health benefits of exposure to green spaces and biodiversity (including microbial diversity). "Green spaces" and "natural environment" will need explicit measures in research at this critical intersection, to enable the development of urban planning strategies in ways that maximize co-benefits associated with cognition, emotion and sensation. In doing so it will become a part of a more comprehensive approach to addressing the growing global burden of NCDs, including inflammatory, immunoregulatory and other conditions.

Box 1. Enabling environments for mental health rehabilitation

Research by Jenny Roe and Peter A. Aspinall has indicated that some environments may be more favourable to mood and cognitive recovery in people with severe mental health problems than others. They compared the restorative benefits of walking in urban and rural settings in a group of adults with a range of mental health problems, including people with schizophrenia and other psychotic disorders (*N*=24). Two aspects of psychological restoration were examined, firstly mood, and the other using personal project techniques (Little 1983) to capture cognitive reflection on everyday life tasks. Participants walked in small groups of around 8 in a variety of urban and rural settings in central Scotland. As anticipated – and consistent with restorative theory – a walk in a natural setting was advantageous to mood recovery and cognitive reflection on the management of personal projects. However, contrary to other evidence showing negative effects of walking in urban settings on people with psychotic disorders (Ellett et al. 2008), in this instance, a walk in a busy historic urban district generated a positive change in mental well-being.

Supporting qualitative research (via semi-structured interviews) (*N*=24) indicated stronger preferences for walking in the natural setting further afield, as compared to walking in the hometown; being away from their everyday environments allowed mental health patients to escape stigmatization and facilitated anonymity. Symptom relief from psychosis and schizophrenia included a reduction in auditory hallucinations (i.e. hearing noises) in the natural setting.

The research concludes that walking in some urban environments (for example, historic districts and city green spaces) – as well as further afield natural settings – offers the potential to promote physical activity and mental well-being in people with severe mental health problems (Roe and Aspinall 2011b). These findings have in general informed UK health policy and in particular initiatives such as the Scottish Government's "green prescriptions" and the Green Exercise Partnership between the National Health Service (NHS) Health Scotland, Forestry Commission Scotland and Scottish Natural Heritage, which are designed to promote greater use of the outdoors for better health and quality of life.

Box 2. Designing for a healing environment: Khoo Teck Puat Hospital, Singapore

Khoo Teck Puat Hospital, a 590-bed acute care hospital in Singapore, aptly presents a case where urban greenery, including biological complexity in terms of species richness and habitat heterogeneity, has been incorporated into the hospital design to reap the associative benefits of healing and well-being. The hospital's concept of "a healing environment" emphasizes the nexus between greenery and well-being in three aspects: first, direct benefits of greenery towards the healing of patients; second, capitalizing on the nexus to improve the livability of the urban environment for both the individual resident and the community; and third, promoting biological complexity in terms of a biodiverse and heterogeneous environment that also contributes to human well-being.

The wards and corridors of the hospital are designed to support patients in the healing process. At ground, the nexus between biodiversity and well-being is explored through the richly planted parklands and the Yishun Pond, whose lush environs are attractive not only to patients and visitors, but also to residents in the surrounding neighbourhoods. The promenade along the edges of the pond and the hospital gardens connects to the adjacent housing estate and train station beyond the hospital grounds, providing seamless access to the surrounding communities. The gardens have attractive water features, including a designed cascading waterfall, adding sound and movement to the environment.

To extend the concept of integration with the community, a rooftop farm grows food crops that are tended by community volunteers and former patients. The crops provide a relatively cheap source of organic food of approximately 208 kg per year for the hospital kitchen, while the harvesting and sale of produce to the public contributes to the hospital green fund. There are over 50 species of fruit trees, and 50 vegetables and herbs in this rooftop farm. The volunteers get to socialize, and bringing their harvest home is both a source of pride and joy, and a therapeutic activity, particularly for the older volunteers who are mostly retirees.

The planting in and around the hospital emphasizes biodiversity and habitat heterogeneity, particularly in terms of birds and butterflies, and fruit trees. In the pond, 100 species of South-East Asian tropical fish have been recorded, some of which were thought to have become extinct. There are reported sightings of 48 species of birds, 44 species of butterflies and 21 species of dragonflies and damselflies. The "medicinal garden" has over 100 species of medicinal plants used in traditional medicine. The pond with its flowering plants at the edges, and its floating mounds, attracts butterflies, dragonflies as well as bird species, which in turn feed on the fish, creating a microecosystem of its own.

The hospital epitomizes the idea of a healing environment in its numerous design dimensions and innovations. It exemplifies an urban asset that goes beyond incorporating landscapes for their aesthetic qualities, and also purposefully and meaningfully seeks to bring biodiversity into urban spaces, all of which contribute to a pervasive sense of well-being that extends to the surrounding community.

Alexandra Health are acknowledged for their input and support. For further information on the gardens and landscaping, see Alexandra Health (2010).

3. Biodiversity, green space, exercise and health

The relationships between biodiversity and good physical health are inherently complex and multidimensional, with multiple confounding and interrelated sociocultural, geographical and economic mediators. The studies that exist often fail to provide clear empirical evidence of the effects of biodiversity on physical health and well-being. While the majority of studies presented herein are examples of where a potential positive association between biodiversity and physical health could be inferred, a large number of studies also report inconclusive results (Lovell et al. 2014) and some report inverse relationships (Huynen et. al 2004; Dallimer et al. 2012). Further multidisciplinary study is needed to more clearly establish causal links to inform policy. Current analyses are methodologically diverse and frequently focus only on urban and western settings that are insufficiently interdisciplinary to test postulated relationships. Research needs to have adequate involvement of the expertise and standard methodological practices of the social sciences (including psychology and sociology), health sciences (including physiology and epidemiology) and environmental sciences (particularly ecology), rather than be dominated by selected disciplines, as is so often the case. In the few studies in which a direct causal relationship between biodiversity and physical and mental health has been sought, it is frequently the case that precise physiological elements of physical health have not been correspondingly measured. With notable recent exceptions, including those noted above, few studies rigorously measure both biodiversity and specific physiological effects on physical health. In addition, the evidence we have is from mostly affluent urban Western societies, and further exploration across a range of cultures, geographical regions and socioeconomic groups is needed, including rural and developing world settings.

3.1 Biodiversity, recreation and leisure, and physical fitness

"Time spent directly experiencing and interacting with nature (a problematic term to define) has been shown to improve psychological health and well-being, as well as increase physical activity levels…" (Pretty et al. 2008).

As human societies industrialize and urban centres continue to expand, the physical relationship with biodiversity sometimes shifts from a direct consumptive interaction to one of more abstracted recreational and leisure activity (Keniger et al. 2013). Regardless of our socioeconomic status, setting or motivations of subsistence or leisure, our exposure to and interactions with biodiversity range from passive engagement from afar (e.g. viewing through a window) to being within a natural space (e.g. sitting in a park), to the direct active engagement of fishing, hunting or gardening. Much of our current body of evidence documenting the health effects of exposure to natural biodiverse environments is gleaned from urban, Western, developed world settings (Lovell et al. 2014; for a recent review, see Townsend et al. 2015). While biodiversity has rarely been measured directly in these studies, they do provide emerging evidence that interacting with natural surroundings in urban settings can deliver a range of measurable benefits (Bauman 2004; Brown et al. 2007; Blair & Morris 2009), including positive effects on physical health (Berger & Motl 2000; Street et al. 2007; Rethorst et al. 2009), psychological well-being (Barton & Pretty 2010; Kaplan & Kaplan 1989; Kaplan 1995), cognitive ability (Ulrich 1983) and social cohesion (Maas et al. 2006). Conversely, there is empirical evidence at a global scale that more biodiverse settings correlate with poorer health outcomes (Huynen et. al 2004) and on a local scale, some self-reported measures of well-being are inversely related with natural biological diversity (Dallimer et al. 2012). While interacting with nature can deliver health benefits, the converse is also true and the specific role of biodiversity in effecting these health outcomes is still not well understood.

It is clear that exercise and physical activity have positive impacts on health. Physical activity has been shown to lead to improved physical fitness and health (Bauman 2004; Brown et al. 2007; Blair & Morris 2009), including a reduced risk of several NCDs, as well as improved immune function. Engaging in regular physical activity has also been linked to improved mental health, including lowering depression, through a combination of physiological effects as well as through increased social engagement (Berger & Motl 2000; Street et al. 2007; Rethorst et al. 2009). Significant proportions of the global population are experiencing epidemics of NCD, including heart and other circulatory diseases, diabetes type 2, and mental health disorders (Beaglehole et al. 2011; Collins et al. 2011). Particularly in urban settings, the management and prevention of some NCDs may be linked to the use, for recreational and fitness purposes, of natural environments or "green spaces", as outlined below. The policy implications for such a linkage are clear: as the global population becomes increasingly urbanized, cross-sectoral consultation between different sectors, including the health, conservation, transport and other sectors, will be key to the development of healthy and sustainable urban landscapes (Box 3). As the chapters on climate change and sustainable consumption in this volume indicate, evaluating and monitoring cumulative health impacts that may result from policy prescriptions (including as they relate to urban planning) will therefore be critical. This includes the need for infrastructure and policy measures, in both developed and developing countries, that support active transit, reduce our reliance on fossil fuels, and concretize the goal of an "urban advantage", which itself "must be actively created and maintained" through robust and coherent policy interventions (Rydin et al. 2012).

Access to parks and green spaces within urban residential neighbourhoods has been shown to be an important conduit to generating better physical and mental health for individuals and communities (Kessel et al. 2009; Maas et al. 2006; O'Campo et al. 2009). Urban parks and green spaces provide places for sport and active recreation, places to relax and enjoy solitude, places to meet other people and socialize, and places that evoke feelings of connection to the natural world (Maller et al. 2008). A reduction in the prevalence of several

Box 3. Urban design for active transport and a healthy human habitat

The urban landscape has become the prototypical human habitat. Commuting by foot or bicycle, so-called "active transport", offers the dual benefits of reducing air pollution emissions – a key driver of anthropogenic climate change – and promoting opportunities for personal fitness. Physical inactivity is a risk factor for NCDs and is estimated to be responsible for 3.2 million deaths annually (Lim et al. 2013). Many studies show significant global health benefits from shifting to environmentally sustainable practices. For example, active commuting in Shanghai, China, reduced risk of colon cancer by 48% in men and 44% in women (Hou et al. 2004), and active transport led to an 11% reduction in cardiovascular risk across sample populations from Europe and Asia (Hamer and Chida 2007). If active transport scenarios reached the levels of those in Copenhagen, costs averted for England and Wales NHS would approximate US$ 25 billion over a 20-year period (Jarret et al. 2012). In the United States (US), comparing cities with the highest versus lowest levels of active transport, obesity and diabetes rates were 20% and 23% lower, respectively (Pucher et al. 2010), and over 1200 lives could be saved annually in the upper Midwest, US, by replacing short car trips with bike transport (Grabow et al. 2012). More public health benefits in developed countries accrue from greater levels of exercise (Grabow et al. 2012; Pucher et al. 2010; Woodcock et al. 2009; Maizlish et al. 2013; Hankey et al. 2012), whereas in low-income countries with air quality problems, the benefits are more from reduced air pollution (Woodcock et al. 2009). Pathways and bikeways in parks and other green spaces will facilitate the adoption of active transport as a viable alternative.

NCDs and their risk factors can be linked to the quantity, proximity and usability of "natural" spaces in the local (residential) environment (Carter & Horwitz 2014; Bowler et al. 2010; Lachowycz & Jones 2011; Lee and Maheswaran 2010; Mitchell and Popham 2007, 2008). Results suggest that perception of park quality is one important factor in encouraging their use for physical activity (Crawford et al., 2008), lowering psychosocial distress (Francis et al. 2012), and supporting better self-reported general health and physical function (Carter & Horwitz, 2014). Bjork et al. (2008) showed that participants with "lush" environmental features within 300 m of the home engaged in greater self-reported physical activity than those with other environmental feature types. Similarly, de Jong et al. (2012) detected a positive association between "lush" environments and physical activity, although Annestedt et al. (2012) noted no association. Tilt et al. (2007) also found positive associations between walking and subjective assessments of overall "greenness." Other relevant findings include proximity to large neighbourhood parks being positively associated with increased physical activity (Giles-Corti et al., 2005), neighbourhood greenness being positively associated with increased walking, social coherence and local social interaction (Sugiyama et al. 2008), and with reduced body weight (Pereira et al. 2013), improvements in park infrastructure resulting in increased use (Veitch et al. 2012 and Veitch et al. 2014), and how the design of open spaces may influence the type of use and length of stay (Goliˇcnika & Ward Thompson 2010). A concerted effort is being made by some governments to maximize these health benefits through park management (see Box 4).

Box 4. Active in Parks Program, Victoria, Australia

The Active in Parks Program forms partnerships between park managers and health and community service agencies to connect people to parks and open spaces to improve physical and mental well-being. The outreach is through tailored activities that increase people's physical activity and overcome barriers, such as transport, lack of awareness and fear, to support their access to parks and other natural open spaces.

The Program commenced in 2010 as a pilot in Geelong, a major regional city in Victoria, Australia. It addresses a number of key health issues, including social isolation, mental health, physical inactivity and priority chronic diseases. Geelong is an area with a prevalence of preventable diseases, particularly in low socioeconomic communities, and is surrounded by outstanding parks and open spaces that are now part of the solution to getting more people more physically and socially active more often, and improving individual and community health and well-being. This is the "Healthy Parks Healthy People" approach to park management.

The Program includes five elements:

Green referrals: physically inactive people at risk of developing or already suffering from chronic illness are referred by their health professional to a physical activity programme based in local parks. They are supported by qualified instructors and encouraged to do ongoing exercise.

Welcome to new migrants: park outings involving physical activity, such as surfing, fishing and beach walking, help newly settled Victorians from diverse cultural and linguistic backgrounds to independently engage in physical activity outdoors and reduce their risk of being socially isolated.

Youth park ambassadors: secondary school students at risk of developing a mental illness and/or disengaging in school take part in outdoor adventure activities to build confidence, resilience and connection with nature, then encourage others to get "Active in Parks".

Adolescent education: young people with type 1 diabetes learn how to manage their chronic illness and treatment while being physically active in nature and making social connections with others.

Parks walks: regular, volunteer walking groups enjoy parks and open spaces, while strengthening community connectedness and encouraging regular outdoor enjoyment of nature.

Participants have credited the Program with restoring their confidence, improving their motor skills and, most importantly, giving them a more positive attitude towards physical activity. Post-Program surveys have unanimously rated the contribution of the Active in Parks Program as beneficial to health and well-being.

Almost 100% of Program participants from July 2013 to December 2013 reported gaining friendships from the Program, with 30% of participants now meeting independently on a regular basis. In 2014, over 66% of respondents reported that the Program increased the time they spent in a park, and over 86% reported that the Program changed their attitude/behaviour towards physical activity. Over 93% of respondents planned on continuing to exercise on their own.

Whereas some studies show that the use of and exposure to the natural environment is associated with better health (Keniger et al. 2013; Lee et al. 2011; Thompson-Coon et al. 2011), others more explicitly link "condition" of the environment to particular health outcomes (Cummins et al. 2005; Mitchell and Popham 2008; van Dillen et al. 2012). Environmental decline, including loss of biodiversity, has also been shown to have greater adverse health effects, particularly on mental health, than the impacts associated with economic decline, nutritional threats and pollution (Speldewinde et al. 2009).

This evidence suggests that among populations for whom access to natural green spaces is limited, such as those in poorer inner-urban areas of large cities, improving that access can encourage regular physical activity, improve life expectancy and decrease health complaints. The psychological benefits and social outcomes may also increase motivation to further exercise and use the green space. Much of this is thought to be due to the perceptions of favourable environmental conditions for people to exercise, thus improving motivation to continue physical activity. Despite the evidence that urban "green" space can increase physical activity and contribute to other dimensions of health, little explicit consideration has been given to the importance of the biodiversity itself (versus simply green or natural space) in delivering improved physical function or health.

We have scant evidence from studies in which standard ecological survey methodology has been undertaken alongside an assessment of physical health. These few studies measure physical health as subjective well-being rather than measuring specific physiological attributes that reflect physical fitness or well-being. An urban Australian study found that personal well-being and neighbourhood satisfaction were positively related to greater species richness and abundance of birds, and with increased vegetative cover and density (Luck et al. 2011). In urban UK, Dallimer et al. (2012) and Fuller et al. (2007) also showed that bird species richness was positively associated with measures of well-being, while butterfly species richness was not shown to have any association. Fuller et al. (2007) found that enhanced well-being was positively related to increased plant species richness, whereas Dallimer et al. (2012) showed a decline in well-being under such conditions. Variation was also seen in relation to tree cover, with Dallimer et al. (2012) reporting a positive relationship with well-being and Fuller et al. (2007) finding no association. Local-scale urban studies on the links between biodiversity in green leisure spaces and self-reported well-being do suggest that exposure to biodiversity may have demonstrable positive impacts on health (Dallimer et al. 2012; de Jong et al. 2012; Fuller et al. 2007; Tilt et al. 2007), although without understanding the specific effected aspects of physiological health. These variations may in part be explained by differing cultural contexts, and even by differences in how various groups within a community value their local landscapes, biodiversity or green spaces. Such perspectives may in part be informed by socioeconomic factors, or by the degree to which different groups feel they can influence local decision-making affecting their environment (see, for example, Cutts et al. 2009; Ernstson 2013).

Some studies do measure sets of physiological indicators of physical health in relation to natural green space but do not measure biodiversity within these natural settings. There is a growing body of evidence to suggest that interactions with nature can alleviate some of the negative physiological effects of stress within urban environments. A study from the Netherlands showed that outdoor gardening led to significantly greater reduction in the stress hormone cortisol than indoor reading (Van den Berg & Custers 2011). This study cannot, however, determine the relative importance of the activity associated with the gardening and the natural components of the environment (e.g. biodiversity) in promoting stress reduction. Some studies have concluded that the physiological effects of stress are reduced in forest environments and other natural environments.[5] For example, a Swiss study also found that a decrease in stress-induced headaches was significantly related to physical activity in parks (Hansmann et al. 2007).

Other physiological benefits that have been studied are the relationships between natural spaces and healing. In a study of cholecystectomy patients in the US, postoperative healing time was significantly reduced for patients in a hospital room with a window view of nature in comparison with patients with a view of a brick wall (Ulrich 1984). Patients with a view of trees also required fewer painkillers, received fewer negative evaluative comments from nurses and had fewer postsurgical complications. Another study demonstrates that outdoor therapeutic camping trips reduce the probability of relapse among recovering substance abusers (Shin et al. 2001).

Physiological responses to nature have also been shown to vary according to gender. A UK study shows that cardiovascular and respiratory disease mortality rates among men decreased with increasing green space, with no significant relationship for women (Richardson and Mitchell 2010). Ulrich (1981) found that the positive physiological responses of exposure to nature, as measured by heart rate and alpha amplitude while viewing images of nature, were significantly stronger for women.

Studies on the effects of indoor plants in office and classroom environments have also shown that their presence can improve physical health (Fjeld et al.1998) and reduce the occurrence of illness (Han 2009; Bringslimark et al. 2007).[6] As with

[5] A Chinese experimental study (Yamaguchi et al. 2006) measured stress in healthy males before and after exercise in both a forest and an urban environment using salivary amylase activity as a physiological indicator. Enzyme activity significantly reduced after exercise in forest environments.

[6] A Norwegian study showed that the presence of plants in offices correlated with a reduction in dry skin, hoarse throat, coughing and fatigue, suggesting that the introduction of foliage plants into an indoor environment may reduce symptoms of physical discomfort and improve health (Fjeld et al. 1998). Related studies on the effects of indoor vegetation have found that the diversity and presence of indoor plants in an office (Bringslimark et al. 2007) and a classroom (Han 2009) reduce the occurrence and frequency of time taken off due to ill health.

many of the studies examining this relationship, and noted often already, nature is often not clearly defined, biodiversity is not explicitly measured and there is a lack of studies in rural, developing countries in equatorial latitudes.

3.1.1 The moderating and mediating influence of socioeconomic status and culture

Socioeconomic status (and sociocultural context to a lesser degree) is well established as a determinant of health, with strong associations found between contributory factors such as income and employment or livelihood security, and health and well-being. Similarly, and as noted previously, exposure to and use of environments containing biodiverse elements have been shown to relate to health and well-being. However, it is only recently that the interactions between these two determinants of health – natural environments and socioeconomic status – have begun to be investigated and, therefore, integrated into and considered within socioecological or ecosystem service models.

Epidemiological work (predominantly undertaken in residential urban areas) shows us that there is often a linear relationship between proximity to, or quantity of (biodiverse) natural environments[7] within the residential living environment and health or well-being outcomes (Carter and Horwitz 2014). However, these relationships are potentially confounded by the likelihood that exposure and access to a large quantity of better-quality natural environments is strongly influenced by the greater choices and resources of populations with higher socioeconomic status (i.e. those with higher incomes and social and individual capital – who therefore enjoy better health and well-being – can afford to move to neighbourhoods with larger proportions of green spaces and biodiversity).

A number of studies have investigated whether the presence of larger amounts of green space has a disproportionate impact on the health and well-being of those with the lowest levels of socioeconomic status (e.g. Dadvand et al. 2012; Logan 2015). In the Netherlands, Maas et al. (2006) found the strongest associations between proximity to natural environments and health for people with the lowest socioeconomic status; similarly, de Vries et al. (2003) found stronger relationships for housewives, the elderly and "lower educated" people. Research using UK data found lower rates of income deprivation-related health inequalities in all-cause mortality and circulatory disease[8] among those living in the greenest places (Mitchell & Popham 2008). Importantly, no association was found when considering outcomes unlikely to have an association with greater exposure to natural spaces (deaths from lung cancer and intentional self-harm). Nearby natural environments have also been found to help women in low-income groups to better cope with stress (Jennings et al. 2012). These studies suggest that people with lower incomes and facing other forms of social and economic disadvantage do have better health when exposed to larger quantities of natural environments. It has been suggested that the presence of attractive, high-quality natural environments (in conjunction with various other factors) moderates the health effects of long-term deprivation (Cairns-Nagi & Bambra 2013). Further evidence has underlined the potential importance of the "quality" of the environment; using the results of the UK Census, larger quantities of green space in the living environment were associated with poorer health for those living in suburban low-income areas (Mitchell & Popham 2007). Importantly, it has been found that (e.g. Coen et al. 2006) green spaces are likely to be of poorer quality in lower-income areas.

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[7] The vast majority of this work has not sought to define the characteristics of the natural environment beyond contrasting these "green spaces" with built urban spaces. Also, it is clear that concepts of green space, and discussions of "access to countryside" are not relevant to large numbers of people, including many local and indigenous communities and diffuse rural populations in much of the world.

[8] Outcomes theorized to be influenced by exposure to or use of green spaces, through for instance mechanisms such as physical activity or lowered psychological stress.


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Recognition of these disproportionate impacts of high-quality natural environments and biodiversity to the health of those with the lowest levels of socioeconomic status has led statutory bodies, such as Natural England and the Forestry Commission in the UK, to adopt policies (for instance, Accessible Natural Green Space Standard[9]) encouraging or facilitating greater equity of access.

Such policy interventions are welcome. In many places, there is an inequitable spatial distribution of biodiverse natural spaces (particularly in the urban context) according to socioeconomic status and other cultural and demographic factors (Astell-Burt et al. 2014; Ernstson 2013). If you live in a low-income urban neighbourhood you are likely to have fewer and lower-quality green spaces and, therefore, fewer opportunities to experience and benefit from biodiversity than people in higher-income neighbourhoods. Multiple descriptive studies have also shown strong correlations between neighbourhoods characterized by lower socioeconomic status (or other factors such as high immigrant populations) and proximity to environments with lower levels of biodiversity (Cohen et al. 2006, 2012; Hope et al. 2003; Kabisch & Haase 2014; Kinzig et al. 2005; Martin et al. 2004; Strohbach et al. 2009). Strohbach et al. (2009), for instance, found that wealthier neighbourhoods, which were typically situated close to forests, parks, rivers and high-quality green spaces, had a greater richness of species than poorer neighbourhoods. The differences can be stark. For example, Kinzig et al. (2005) found an average of 28 avian species in parks in high-income areas compared with only 18 avian species in parks in low-income areas.[10]

However, even where policies to facilitate exposure to biodiverse environments are acted upon and efforts are made to improve accessibility, it still may be the case that some groups, particularly those with lower socioeconomic status, face inequitable access (Jones et al. 2009).[11] Similar disproportionate reliance on local environments

[9] 'Nature Nearby' Accessible Natural Greenspace Guidance. www.naturalengland.org.uk

[10] This inequality could, in some cases, have profound implications. Quality of life is strongly influenced by one's environment, particularly for the poor and marginalized who most need access to high-quality, local biodiverse environments, as they are likely to be unable to travel frequently for any great distance to experience these places (Kinzig et al. 2005).

and biodiversity is also found for people with lower socioeconomic status in low- and middle-income countries. While the mechanisms can be fundamentally different, perhaps relating more strongly to other determinants of health such as adequate nutrition and clean water, the ability to access, and to make use of, biodiversity-related resources can have a greater impact on the health and well-being of the poorest members of a particular society (Daw et al. 2011; Millennium Ecosystem Assessment 2005; see also Dallimer et al. 2012). Likewise, the loss of biodiversity is likely to disproportionately impact on the health and well-being of the poorest (Díaz et al. 2006; Raudsepp-Hearne et al. 2010).

Raudsepp-Hearne et al. (2010) explored four potential hypotheses (in relation to global biodiversity loss) to explain why we are not able to consistently show how biodiversity relates to well-being: (i) we may be looking at the "wrong" aspects of well-being, and the ones we have considered may not be sensitive to environmental influences, and that practices such as aggregation could mask shifts in well-being (see also Lovell et al. 2014 and Daw et al. 2011); (ii) our well-being is only actually sensitive to certain environmental influences, particularly those associated with the provisioning services and especially food; (iii) there has been a "decoupling" of human well-being's dependency on the environment through technological and social innovation; other factors such as access to mental health care, the socioeconomic context or just familial circumstances might exert a greater influence than the natural environment. If the environment has a relatively small impact then detecting that influence is difficult and the measures used need to be sensitive; and (iv) well-being will be affected by environmental degradation but we have not yet reached that point, and therefore the impacts of the environment on well-being are not yet detectable.

4. The contribution of biodiversity to cultural ecosystem services that support health and well-being

An accepted characterization for cultural services is provided by the Millennium Ecosystem Assessment (MEA) (2005), described as the non-material benefits people obtain from ecosystems through spiritual enrichment, cognitive development, reflection, recreation and aesthetic experiences, and including ten different forms of values. Given the often discussed overlaps between services, benefits and values, and the consideration of both use and non-use (or non-consumptive) values of cultural ecosystem services, this chapter follows the convention established by Milcu et al. (2013) and others (e.g. Gee and Burkhard 2010) to include existence, bequest and option values, and the intrinsic value of ecosystems as a subcategory of cultural ecosystem services.

In a comprehensive review, Pretty et al. (2008) explored how biological and cultural diversity intersect, describing "nature" as "the setting in which cultural processes, activities and belief systems develop, all of which feed back to shape the local environment and its diversity".[12] There are of course other models that depict pathways between biodiversity, culture, and physical and mental health, but the point made here is that they are extraordinarily diverse, where it is difficult to generalize or to derive universal statements.

[11] For example, Byrne et al. (2009) cite the case of Los Angeles' Santa Monica Mountains National Recreation Area, the result of policies in the 1970s which aimed to "to bring nature and recreational opportunities to socio-economically disadvantaged communities in the USA", but where visitors were found to be predominantly white and affluent. Huynen et al. (2004) describe the association between low socioeconomic status, race and ethnicity and poor access to biodiverse environments as "yet another instance of urban environmental inequality".

[12] They described four key bridges interlinking nature with culture: (i) beliefs, meanings and worldviews that underpin the way humans see their place in nature; (ii) livelihoods, practices and resource management systems, where nature is managed; (iii) knowledge bases and languages, where how people know the world governs behaviours, understanding and values that shape human interactions with nature; and (iv) socially embedded norms and institutions, where normative rule systems govern human interactions and behaviours towards the natural environment.

While many community-specific linkages between health, culture and biodiversity have been documented and measured, much of the evidence for a more universal relationship is sparse beyond anecdotal accounts. However, there is growing recognition of the role of biodiversity and ecosystem services in shaping broad perspectives of the quality of life. The WHO Quality Of Life Assessment (WHOQOL) was devised as a method to determine an individual's quality of life in the context of their culture and value systems; use of the WHOQOL method has shown that the environmental domain – including aspects of safety, security, access to resources and interaction with local environments – is an important part of the quality-of-life concept (WHOQOL Group 1994; see also Skevington 2009).

Clark et al. (2014) conceptualized the *direct* linkages between biodiversity and human health via disease regulation and pollution control, and the *indirect* linkages between biodiversity and human health as being "cultural", where biodiversity yields cultural goods, cultural values are placed on those goods, and when they are derived there is a well-being benefit and therefore a human health outcome.

Culturally competent health practice must account for the influence of culture on attitudes, beliefs and behaviours, including the relationship between people and their local biodiversity and ecosystem services. The relationship between culture and population health is complex. The delivery of primary health care at the community level is generally organized around predominant local cultural norms, but must also increasingly account for cultural diversity and the cultural characteristics of minority groups.

For each of the well-known categories of cultural ecosystem services, it can be demonstrated that biodiversity plays a role in the way physical and mental health and well-being have been or can be derived.

Cultural diversity. Reciprocal relationships have been described between cultural diversity and biological diversity in the diversity of life, at whatever levels of richness; they are inseparable. Formal recognition of cultural diversity has demonstrable health benefits for cultures (often minorities) that have suffered from domination and oppression; replacement with other biological elements might have poorer health outcomes for the same reasons.

Spiritual and religious values. Sacred elements of the biota, worship of biota, kindness and gratitude toward biota together or individually make a contribution to spiritual well-being, and a sense of wholeness and being "at one", everywhere and forever (connecting the present with the past and the future).

Knowledge systems (traditional and formal). This includes knowledge of pharmaceuticals, food products and knowledge contributing to rituals, and socializing processes. These together provide people with understanding on when and where to use biological materials for alleviating poor health or disease, including when and where to use them for better diet and nutrition, and spiritual well-being.

Educational values. Ecosystems and their components and processes provide the basis for both formal and informal education in many societies. These learned capacities provide the ability to avoid environmental hazards and physical injury or death, and to alleviate psychosocial stress-related disorders.

Inspiration. Ecosystems in general, and elements of biodiversity in particular, provide a rich source of inspiration for art, folklore, national symbols, architecture and advertising. These contribute to well-being in a myriad of ways.

Aesthetic values. People find beauty or aesthetic value in various aspects of ecosystems, as reflected in the support for parks, scenic drives and the selection of housing locations. These values have been linked to stress relief, with therapeutic benefits.

Social relations. Ecosystems influence the types of social relations that are established in particular cultures. Sharing ecosystem experiences, like volunteering for land and water rehabilitation or species conservation activities, has been shown to have positive psychosocial outcomes.

Sense of place. Many people value the "sense of place" that is associated with recognized features of their environment, including elements of the biota (rare, common, iconic, endemic) and aspects of the ecosystem. Psychosocial disorders have been described to be associated with the loss of, or inability to derive, solace connected to the present state of one's home environment (see Albrecht et al. 2007).

Cultural heritage values. Many societies place high value on the maintenance of either historically important landscapes ("cultural landscapes") or culturally significant species. Protection of heritage values will enhance cultural recognition, with health and well-being benefits, particularly where done without the continuation of any domination or oppression that might have occurred in the past, allowing the continuation of cultural practices where they have health-related outcomes.

Recreation and ecotourism. People often choose where to spend their leisure time based in part on the characteristics of the natural or cultivated landscapes in a particular area. Recreation also occurs in relation to animals or plants, caring for pets, or gardens, parks and reserves. Health outcomes relate to physical exercise, fitness and the myriad contributions this makes to physical and mental health, and the alleviation of psychosocial disorders.

4.1 Indigenous health and well-being

The key literature on biocultural diversity – the intimate, inextricable links between linguistic, cultural and biological diversity, as manifestations of the diversity of life – demonstrate their overlapping global distributions, and the common threats they face (see the major review on this topic by Maffi 2005): "... the ongoing worldwide loss of biodiversity is paralleled by and seems interrelated to the 'extinction crisis' affecting linguistic and cultural diversity".[13] Maffi reviews the studies that have shown overlaps (also referred to as correlations) between linguistic diversity at the global level, and both vertebrate diversity and plant diversity. Hypotheses explaining this fact are contested but invariably detail the role of sociocultural factors, along with biogeographical factors.

To some, the intricacies of the relationships between linguistic, cultural and biological diversity suggest a co-evolution, or reciprocal development. Gorenflo et al. (2012) suggest that, in many instances, this co-occurrence between biological and linguistic diversity may hint at some form of functional connection – perhaps founded in a need to describe culturally or nutritionally important species, habitats or landscape elements – though there is much local variability and the relationships are complex (see also Gavin and Sibanda 2012; Axelsen and Manrubia 2014).

Pretty et al. (2008), drawing on the work of Berkes (2008) and others, conclude that cultural diversity and biological diversity are reciprocally developed and maintained.[14] The links between language and biodiversity also reflect a wider connection between nature and a community's sense of place. Loss of language, and its concomitant cultural loss, may be a source of considerable demoralization and anguish. In this sense, and assuming the reciprocal relation, biodiversity loss is indirectly or directly associated with these health consequences. Moreover, the links between biodiversity and cultural and linguistic diversity suggest that the protection of human rights can be connected to the affirmation of human responsibilities toward and stewardship over humanity's heritage in nature and culture (Maffi 2005).

[13] Maffi describes the philosophical tradition that regards linguistic diversity as an adequate correlate for cultural diversity, citing Harmon's work that the perception of diversity is the basic condition for the functioning of human consciousness, and Wollock's observation that all great metaphysical traditions recognize endless diversity as the reality of the planet.

[14] "How we know the world... governs our behaviour and practices that, in turn, shape landscapes, which form a cultural archive of human endeavours. Amidst a diversity of cultures comes a diversity of meanings, leading to a diversity of actions, providing an array of biodiversity outcomes." (Pretty et al. 2008)

Therapeutic and biocultural landscapes are an important dimension to achieve health at the local level. Survival and vitality of knowledge and resources depend on the sociocultural contexts in which they are embedded (see also the chapter on traditional medicine in this volume). Typically, such knowledge and resources are found to be most vibrant among communities (specifically, indigenous and local communities) close to culturally important landscapes. These could relate to socioecological production landscapes (e.g. Satoyama in Japan) or conservation systems (e.g. sacred groves, ceremonial sites) or therapeutic landscapes (such as sacred healing sites). Such landscapes and related traditional knowledge practices contribute to health and well-being, therefore necessitating a close inquiry into the functional interlinkages within such systems, and maintenance of their dynamism.

As described in the chapters on nutrition and traditional medicines, indigenous peoples are often a potent symbol of our human diversity of culture, language and spirit. Many have also been the guardians of our global biodiversity and its medicines, foods, shelter and spiritual resources for millennia – built on a holistic communal view of humanity and its links to the ecosystem. Yet now, in the new millennium, indigenous peoples are among those most marginalized within many nation states, they have the worst health indicators, and their knowledge is fast disappearing as their land is appropriated and their environment destroyed.

But indigenous peoples also often have an intimate knowledge of the other valuable living resources available in their biodiverse settings – including medicines and foods that are vital for global and local health (Box 5, Box 6). Instances where indigenous peoples have retained a profound connection to the land and water and living components of their territories, and instances where socioeconomic and political forces have combined to alienate indigenous peoples from their cultural values and traditions, both demonstrate the saliency of connections across biodiversity, cultural knowledge, and human health and well-being.

Box 5. Biodiversity, essential for Mbya Guarani well-being and health

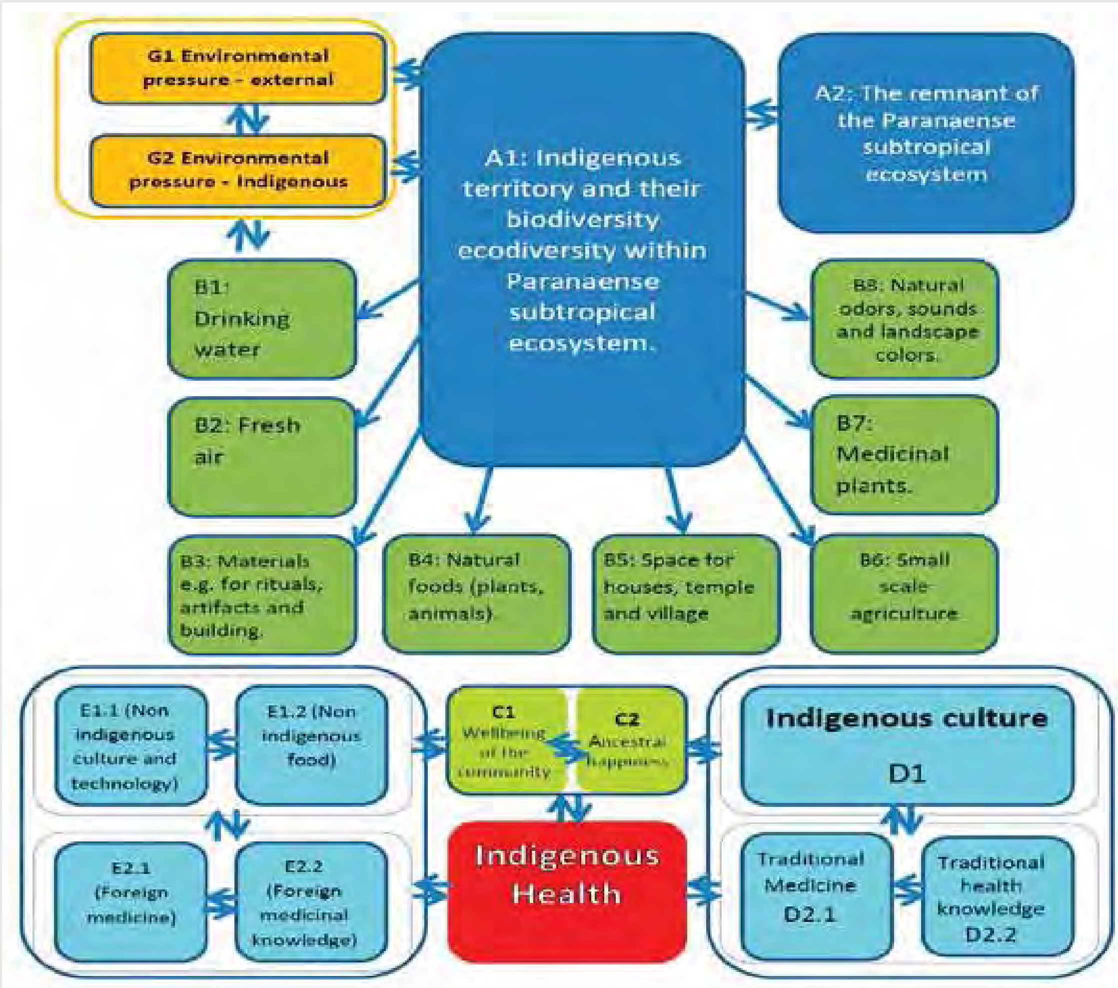
Those indigenous people that survive as hunters, gatherers and small-scale agriculturalists display complex relationships between territory, biodiversity and ecodiversity (Montenegro 1992; 2006). Among the Mbya Guarani who live in relatively self-decided isolation, like the communities of Tekoa Yma and Tekoa Kapi'i Yvate in the subtropical forest of Yaboti (Misiones, Argentina), their well-being and health system is the result of complex sustainable interactions. The main variables involved are growing knowledge of the social and natural environment, efficient intergenerational transmission of information, entire life educative schemes, lack of permanent private property and adaptive nomadic behaviour. Their dominant long food chain strategy ensures direct and seasonal relationships with different arrangements for biodiversity. Contemporary communities use, for example, 150 species of medicinal plants, 35 plant species and 94 animal species as food, 54 species as raw materials for rituals, artifacts, weapons and building, and 61 species as fuel (biomass) (Keller 2001; Montenegro 2004). Deforestation and biodiversity loss, mainly produced by foreigners, negatively affects not just their health system but also their rituals and well-being. *Ñemongarai*, the ceremony where the *opygua* (= shaman) delivers names to children, demands – for boys – fruits of *guembe* epiphyte (*Philodendron bipinnatifidum*) and honey from the wild bee *jate'i* (*Tetragonisca angustula*). Their growing scarcity in Yabotí, as a result of biodiversity reduction, distresses both families of children and the community (Montenegro 2004). Currently, most indigenous peoples develop hybrid strategies that combine both traditional and foreign medicine (*cf.* Montenegro & Stephens 2006).

Indigenous well-being and health system are the result of "n" interacting variables organized in seven Boxes (Figure 1), where biodiversity plus ecodiversity of the territory (A1) and of remnant

Parananse ecosystem (A2) are essential. Approaches that do not consider this minimum organization of variables are unreal and cannot represent the complex source of indigenous well-being patterns (Montenegro 2004).

FIGURE 1: Indigenous peoples health and the ecosystem

Group A: The ecosystem. A1: Indigenous territory and its biodiversity plus ecodiversity (>6000 hectares for *Tekoa Yma* and *Tekoa Kapi'i Yvate*) within Paranaense subtropical ecosystem. A2: The remnant of the Paranaense subtropical ecosystem (less than 5% of the original surface in Brazil and Argentina). **Group B: Resources obtained from the ecosystem.** B1: Drinking water. B2: Fresh air. B3: Materials, e.g. for rituals, artifacts and building. B4: Natural foods (plants, animals). B5: Space for houses (*oo*), temple (*opy*) and the *Tekoa* (village). B6: Small-scale agriculture (mainly maize). B7: Medicinal plants. B8: Natural odours, sounds and landscape colours. **Group C: Well-being of the community**, C1, and C2: "Ñande reko", ancestral happiness. **Group D: Indigenous culture** D1, which includes D2.1: Traditional medicine and D2.2: Traditional health knowledge. **Group E: Foreign culture**, which includes E1.1: Non-indigenous culture and technology, E1.2: Non-indigenous food; E2.1: Foreign medicine and E2.2: Foreign medicinal knowledge. **Group F: Indigenous health. Group G: Environmental destruction and biodiversity loss by deforestation, hunting and other activities;** G1: Environmental pressure (external, generated by foreign people and companies); G2: Environmental pressure (internal, of indigenous activities, usually more diluted).



Source: Adapted from Montenegro 2004

Box 6. Ko Omapere te wai, Aotearoa (New Zealand)

The largest lake in Northland, Omapere (1197 ha), once a wetland forest, is shallow (2.6 m) and feeds the Utakura River that flows west to the Hokianga Harbour. Omapere is a *taonga* (treasure) to Ngapuhi, who maintain *manawhenua* (ownership) and *kaitiaki* (guardianship) rights and responsibilities through indigenous leadership. Ngapuhi have fought for the protection of Omapere, articulating the significance of its ecological integrity: *use of the lake is determined by the health of the lake; the health of the lake and the health of the people are intertwined* (Henwood and Henwood 2011).

Omapere was a "food basket" that supplied *tuna* (eel), *torewai* (freshwater mussels) and other resources, including *raupo* (bulrush), *kapangawha* (clubrush) and *harakeke* (flax).

Clearing of native vegetation and dairy farming in the surrounding catchment led to dense growths of invasive oxygen weed (Tanner et al. 1986) that eventually collapsed, leaving Omapere turbid and algae dominated (Champion and Burns 2001). In 1985, the Northland Area Health Board advised the municipality to abandon its water for domestic supply due to a severe cyanobacterial bloom that polluted the Utakura River and upper reaches of the Hokianga, leaving traditional fish and shellfish stocks unsafe to eat (Grey 2012).

In 2004, tribal leadership brought together community stakeholders and responsible agencies to identify restoration and management strategies, implement monitoring and fishing regulations, and commission studies. The *ma uta ki tai* (catchmentwide) process adopted emphasized the physical and social interconnectedness of waterways and human activities, and recommended integrated solutions. Community-led fencing of the lake edges, riparian planting and a local species nursery plus farm environmental plans reduced fertilizer run-off and dissolved nitrogen and phosphate levels (Grey 2012).

There have been no algal blooms in the lake since 2007 and recent improvements in water quality have been linked to increased water-filtering *torewai* populations (Grey 2012). Many customary community practices of water use in the catchment have resumed and in 2011 *tuna* returned to the tables of Mokonui-a-rangi Marae, welcoming guests with this traditional *kai* (food) for the first time in more than a decade.

4.2 Biodiversity and local and community health and well-being

Biodiversity is often central to cultures, cultural traditions and cultural well-being. Species, habitats, ecosystems and landscapes influence forms of music, language, art, literature and dance. They form essential elements of food production systems, culinary traditions, traditional medicine, rituals, worldviews, attachments to place and community, and social systems. The divisive nature of modern societies is evident in the gaps between the rich and the poor, the able-bodied and those with disabilities, the employed and the unemployed, and these are increasingly obvious in government policies and in life experiences. These divisions not only undermine individual health and well-being, but may also threaten community cohesion, including among indigenous and local communities.

As discussed in the chapter on traditional medicine, indigenous and local communities often act as stewards of local-living natural resources based on generations of accumulated traditional knowledge, including knowledge of agricultural biodiversity, and biodiversity that supports traditional medicinal knowledge. Where local traditions and cultural identity are closely associated with

Box 7. Biodiversity, physical health and community well-being

The "Feel Blue, Touch Green" project (Townsend & Ebden 2006) in 2005 engaged people experiencing depression and/or anxiety in hands-on conservation activities in partnership with ANGAIR (the Anglesea and Airey's Inlet Society for Protection of Flora and Fauna). Participants committed to 10 hours of conservation activities over 5–8 weeks, and the project and its impacts were evaluated using mood scales and in-depth interviews. The results showed that participants experienced positive emotional changes, with the most positive changes being an improved sense of relaxation, higher levels of interest and greater life satisfaction. Participants also scored highly in terms of improved health and happiness. These findings were corroborated through interviews in which participants identified the importance of the context for and the focus of the activities (particularly the emphasis on biodiversity maintenance) in fostering the benefits they were gaining and in transforming their interactions with the natural environment and with other people.

Those "bridging" benefits were echoed in a study in 2007 (O'Brien et al. 2008); using similar evaluation methods, motivations, barriers and benefits of environmental volunteering in southern Scotland and northern England were explored. The groups studied ranged from local groups working with councils or NGOs to restore degraded local environments through to a group of volunteers who had raised £350 000 to purchase a valley in Scotland and were working to return it to the "wildwood" it would have been 6000 years ago! Volunteers typically experienced positive emotional changes on all parameters except pain, and even that was interpreted positively as indicating that they had worked hard, thus contributing to satisfaction!

Face-to-face interviews with volunteers and representatives of the organizations hosting the activities confirmed the individual, community and ecosystem well-being benefits, many of which can be characterized using this notion of "bridging".

However, the most telling example of this bridging across the divides came on the day when four diverse groups came together at Eskdale in the Lake District to do some coppicing (removal of invasive species to allow room for the native vegetation to grow). The volunteers included four persons from "Friends of the Lake District", 10 "Environment Agency" staff members (i.e. corporate volunteers), two Lake District National Park volunteers, and two staff and three residents of West House (a facility for adults with developmental delays).

biodiversity and ecosystem services, declines in the availability and abundance of such resources can have a detrimental impact on community well-being, with implications for mental and physical health, social welfare and community cohesion (see, for example, Box 8).

Efforts to promote and sustain biodiversity have been shown to build bridges across these divides and to offer new hope for individual, community and ecosystem well-being. As the examples in Box 7 indicate, there are many more benefits that flow from human engagement in efforts to restore and maintain biodiversity through environmental volunteering. Key among them is connectedness: to our own inner beings, to others and to the natural environment; revisiting calls for "reciprocal maintenance" that have been foundational to health promotion since the Ottawa Charter (WHO 1986; Parkes and Horwitz 2009).

Box 8. Psychosocial health and fish biodiversity in Fiji

The high biodiversity ecosystems within the Pacific are the settings for health where cultural identity, subsistence life and social systems exist (*sensu* Horwitz and Finlayson 2011). In a set of studies from the small-island developing state of Fiji, Jenkins et al. (2010) demonstrated the notable absence from degraded river basins of suites of fish that traditionally formed the staple diets of inland communities. Notably absent species in heavily modified catchments include many migratory species that form important commercial and cultural fisheries for Pacific islanders. These effects are largely seasonal and magnified in degraded catchments, with pronounced negative impacts on food-provisioning services and biodiversity during heavy rainfall and severe storms (Jenkins & Jupiter 2011). These effects will likely become more severe under predicted future climate scenarios. Community bans on harvesting and clearing within riparian wetlands can be effective in maintaining fish diversity, even in areas where forests have previously been extensively cleared (Jenkins et al. 2010). However, these benefits are rapidly lost once the ban is lifted and fish from rivers again become scarce (Jenkins & Jupiter 2011). Fresh fish often contributes more than 75% of the fish consumption of both rural and urban areas of the Pacific, with the remainder comprising canned fish (Bell et. al 2009). Given the high levels of fish consumption, and the limited opportunities for agriculture and animal husbandry in small islands, fish usually contributes the majority of animal protein in the diet at the national level (Bell et al. 2009). For many Fijian inland communities, freshwater fish not only comprise a major part of the diet but also have important cultural totemic values. Loss of freshwater fish biodiversity therefore has important implications for physical and cultural well-being. Some authors note an ecology-driven model of well-being in many Pacific islands that is based on the vitality and abundance of natural resources relied upon for subsistence and cultural practices (McGregor et al. 2003). Within this ecological model, the collective family unit forms the core social unit within which the individual lives and interacts, which is interdependent upon the lands and associated resources for health (physical, mental and emotional) and social well-being. This case illustrates the potential for physical and psychosocial health to be effected through loss in fish biodiversity. However, like many studies, while biodiversity loss can be clearly demonstrated, the precise nature of impact on physical health through nutritional or cultural deficit has not been investigated.

5. Conclusions and ways forward

This chapter has presented an account of evidence that suggests that biodiversity plays a role in people's lives, in their cultural traditions and in their social interactions, and that health outcomes are a consequence of these relationships.

Species, habitats, ecosystems, and landscapes form essential elements of food production systems, culinary traditions, traditional medicine, rituals, worldviews, attachments to place and community, and social systems. The constructs of cultural ecosystem services, and ecosystems as settings, can be used to frame the relationships between biological diversity and cultural diversity, and human health and well-being. The cultural services provided by an ecosystem provide a useful lens through which the interlinkages between biodiversity and health can be seen.

Over half of the world's population already lives in cities and the transition toward urban and peri-urban areas is steadily increasing, which will be a major challenge for all countries, with notably pronounced impacts in developing countries (UN-Habitat & UNHSP 2010; Cohen 2006; Cohen et al. 2012; Montgomery 2008). There is a rising trend for people, especially within poor communities, to be separated from nature and

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to be deprived of the physical, physiological and psychological benefits that ecosystems provide (Sandifer et al. 2015). This is not insignificant in the context of the shifting global burden of disease, in which NCDs continue to account for an increasing proportion of the burden. At the same time, the rise in physical inactivity, combined with dietary changes that often accompany the transition from rural to urban and peri-urban areas, also importantly contribute to the burden of NCDs. These rising challenges present new opportunities to produce benefits for biodiversity conservation and public health, through:

– urban planning to encourage active transport;

– building designs that enhance local environments and cultural traditions;

– creating settings for restorative health that draw upon cultural ecosystem services; and

– a deeper understanding of the ways in which positive and negative exposures to biodiversity are felt by individuals.

Exploring these associations has been, and needs to be, an interdisciplinary and cross-sectoral pursuit. In some instances, an empirical and/or rational inquiry will demand and reveal evidence to demonstrate a particular relationship, much like that expected of sound epidemiological or immunological analyses. In other instances, the relationship is explored with spiritual, emotional or intuitive worldviews, informed by the social sciences. Research from all of these disciplines will provide for a comprehensive treatment of the subject.

The diverse and interrelated implications of the cultural appreciation of biodiversity for well-being, including outcomes for physical and mental health, are embraced by interlinkages that range from obvious, direct and linear ones, to ones that are indirect and more complicated, often mediated by socioeconomic factors and issues of scale, to ones that are more reciprocal, where biodiversity, culture and human health are interdependent.

The interlinkages can be obscured or confounded by the trade-offs of natural capital for other forms of capital, such as built, infrastructural and financial. While trade-offs are sometimes inevitable and even necessary, these other forms of capital often give a shorter-term well-being benefit, even though ecosystem services may have been degraded and biodiversity may have been lost. Exploring further interdisciplinary study of the interlinkages between biodiversity, physical and mental health, and cultural ecosystem services provides both a framing device for the post-2015 sustainable development goals, and a set of integrated indicators that will allow targets to be set.

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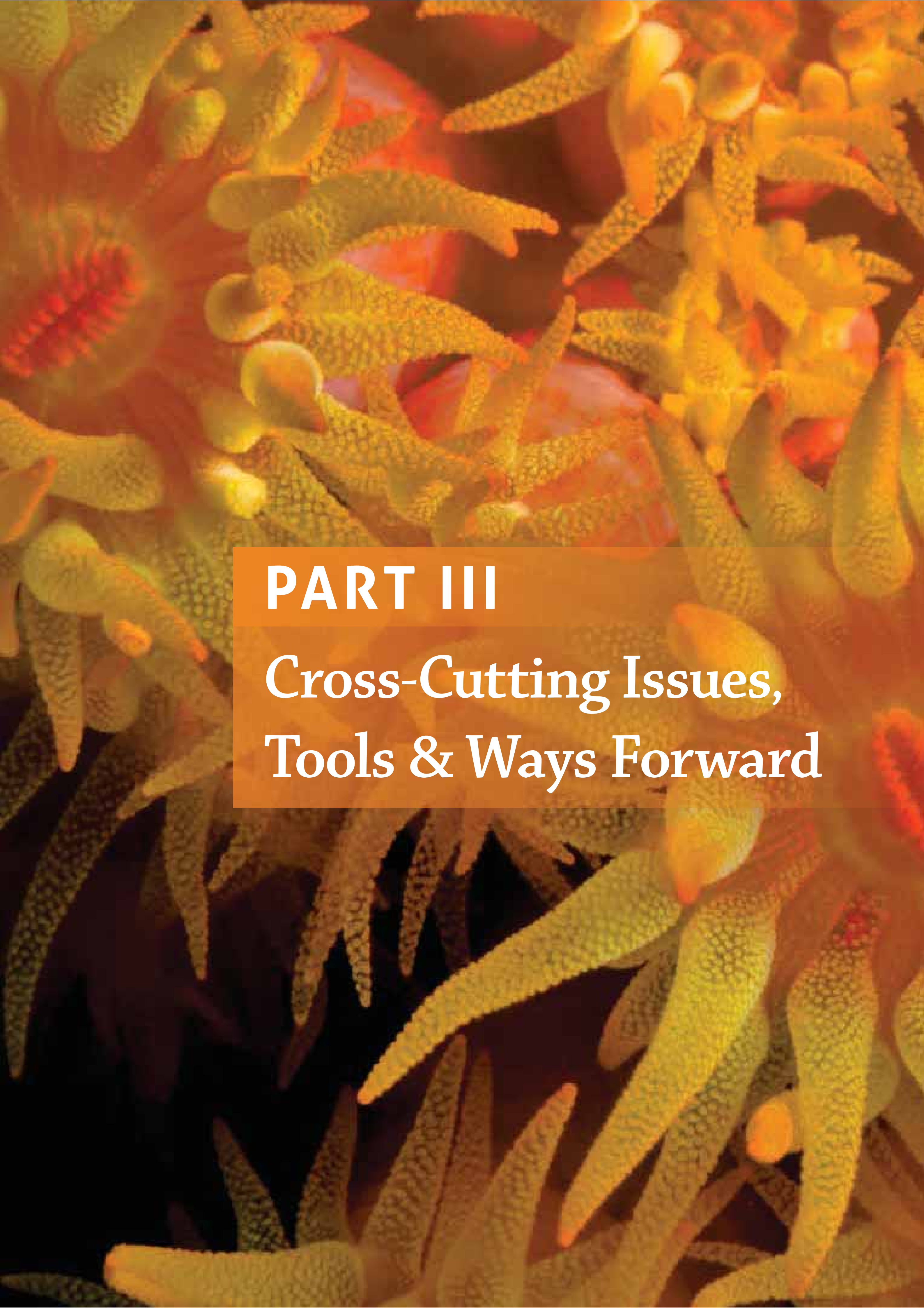
PART III

Cross-Cutting Issues, Tools & Ways Forward



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13. Climate change, biodiversity and human health

1. Introduction

Climate change is one of the greatest challenges of our time. It is now widely recognized that climate change and biodiversity loss[1] are interconnected, and that both are increasingly influenced by human activity (IPCC 2014; Pereira et al. 2010; Campbell et al. 2009; Bellard et al. 2012; Parmesan et al. 2011; Rockström et al. 2009; Beaumont et al. 2011; CBD 2009, 2003). The recently released Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) supports previous findings that climatic change will probably be perilously aggravated unless robust climate adaptation and mitigation measures are adopted.[2] Total greenhouse gas (GHG) emissions[3] resulting from anthropogenic activity have risen more rapidly between 2000 to 2010 than in any other period in human history (IPCC 2014b),[4] and the potential impacts of anthropogenic activity on biodiversity under business-as-usual scenarios are but another reminder of the critical need for action (CBD 2010; 2014). The impacts of climate change will be amplified as it interacts with a range of other drivers; a warming climate not only threatens the stability and functioning of our planet's biological and physical systems but also poses direct and indirect threats to global public health, with more pronounced impacts on the world's most vulnerable populations (McMichael et al. 2006, 2012; Parmesan and Martens 2009; Haines et al. 2006).

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1 The Fifth Conference of the Parties (COP) to the CBD highlighted the risks of climate change, in particular, to coral reefs (decision V/3) and to forest ecosystems (decision V/4), and drew attention to the serious impacts of biodiversity loss on these systems and their associated livelihoods. The cross-cutting issue on biodiversity and climate change was included in the work under the Convention in 2004 through decision VII/15 of the COP. Among other subsequent COP decisions on climate change, at its tenth meeting the COP in decision X/20 para 17b requested the executive Secretary to explore avenues for bridging the gaps between work being carried out to address the impacts of climate change on public health and work to address the impacts of climate change on biodiversity.

2 These reports of the working groups and the synthesis report of AR5 are available at http://www.ipcc.ch/report/ar5/.

3 Based on the most recent IPCC estimates, the greatest contributors of greenhouse gases are: CO_2 (76%); CH_4 (about 16%), N_2O (about 6%) and the combined F-gases contribute about 2% (IPCC 2014a).

4 From 2000 to 2010, GHG emissions grew on average 2.2% per year compared to 1.3% per year over the entire period from 1970 to 2000. Moreover, although more recent data are not available for all gases, "initial evidence suggests that growth in global CO_2 emissions from fossil fuel combustion has continued with emissions increasing by about 3% between 2010 and 2011 and by about 1–2% between 2011 and 2012" (IPCC 2014b). By sector, the largest sources of GHG emissions came from energy production, agriculture, forestry and land use (AFOLU), and industry (IPCC 2014a).

The chapters in this volume have drawn attention to a number of risks posed to human societies by the degradation of the earth's ecological and climatic systems, including threats to water and food security, air quality, the availability of natural resources used for medicinal, spiritual or recreational purposes and livelihoods, population displacement, conflict and disasters, and potential influences on patterns of disease. These burdens, however, are not evenly distributed. The greatest impacts often fall upon the most vulnerable populations, including women, children and poverty-stricken communities who are often least directly responsible for global environmental change, yet particularly vulnerable to the risks posed by multiple environmental stresses (Türkeş 2014). They are also, most frequently, the least able to assess and address these risks. Vulnerable communities face a double challenge: the combined effects of climate change and biodiversity loss undermine the partial progress made to achieve the Millennium Development Goals (MDGs), which in turn further weakens not only ecosystem integrity but also country or community ability to respond to these risks.

1.1 Impacts of climate change on human health

Though anthropogenic climate change has been scientifically recognized since the nineteenth century, real interest in the topic began in 1957, during the International Geophysical year, with the prophetic remark that "human beings are now carrying out a large-scale geophysical experiment of a kind which could not have happened in the past nor be reproduced in the future"(Callendar 1958). By the time of the establishment of the IPCC by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) in 1988, this was clearly understood, as the IPCC was called on to assess "the scientific, technical and socioeconomic information relevant for the understanding of the risk of human-induced climate change."

In the health literature, recognition of links between public health and climate change is now over a quarter century old, with pioneering papers in 1989[5] published in the world's two leading English-language medical journals – the Lancet and the New England Journal of Medicine (Anonymous 1989; Leaf 1989). In the latter, Alexander Leaf stated that the "United States, with more than 19,000 km of coastline, will not be spared. For example, much of Florida sits on porous limestone. Miami has such a porous aquifer that a protective dike against rising sea levels would have to start more than 45 m (150 ft) beneath the surface to prevent salt water from welling up behind it. Displaced people and less arable land would compound the problem of feeding the world's increasing population." He added: "Probably the most widespread and devastating consequences of global environmental changes are likely to result from their effects on agriculture and food supplies for the world's burgeoning population" (Leaf 1989).[6]

Health awareness and expertise on the subject of climate change and health was too young for the topic to be explicitly included in the first IPCC report (1990). This was corrected in the second report, shortly followed by publication of the first edited book on climate change and health (McMichael et al. 1996; see also McMichael et al. 2003). The World Health Organization (WHO) – which published the books – continues to play a leading role in developing the topic. Today, the issue of climate change and health attracts widespread interest from the public health sector and is increasingly prominent in the international scientific literature. Increased attention by the scientific community has been accompanied by growing awareness of the issues among broader public and civil society. Some analysts have expressed the hope that a general awakening by the public to the *health* risks of climate change will accelerate the nascent "sustainability transition" needed to ensure the survival of civilization

[5] That same year, the World Health Organization (WHO) set up a task group on the subject and in 1990 published a report on the "potential health effects of climate change". Available at http://whqlibdoc.who.int/hq/1990/WHO_PEP_90_10.pdf

[6] An article published in the Lancet that same year raised the additional possibility of conflict associated with climate change (Anonymous 1989).

(McMichael et al. 2000), even beyond that of commensurate awareness in other disciplines.

The myriad health effects of climate change can be categorized into three broad categories (Butler 2014a): direct, indirect and tertiary. While it is difficult to catalogue all the impacts of climate change on human health, Box 1 summarizes a threefold approach that can help us conceive primary, secondary and tertiary impacts that affect the biodiversity–health nexus.

Box 1. Direct, indirect and tertiary impacts of climate change on human health

Direct

Direct health impacts are those that are directly, causally attributable to climate change and/or climate variability, such as cardiovascular risk associated with heat waves, or risk of injury associated with more intense and frequent storms. The recent findings of Working Group III of the IPCC have indicated, with a high degree of confidence, that the impacts of recent climate-related extremes, including heat waves, droughts, floods, cyclones and wildfires, have already led to vulnerability and exposure of some ecosystems and several human systems to current climate variability. Such extreme weather events impact vulnerable groups such as the poor and elderly the most, though the adverse effects on human health can be ameliorated to a certain extent by social and technological mediators, such as improved urban design and building standards (e.g. Santamouris 2013; Brown and Southworth 2004; Birkman et al. 2010).

Despite scientific argument over whether the witnessed increase in heat waves, fires and adverse crop yields in Eurasia in 2010 were random or had been exacerbated by anthropogenic climate change, the event still directly contributed to 50 000 excess deaths (Barriopedro et al. 2011). The subsequent rise in global grain prices further indirectly impacted human health and food security among vulnerable populations worldwide (Johnstone and Mazo 2011). As such, the effects of climate change on water, food security and extreme climatic events are likely to have profound direct impacts on global public health (Costello et al. 2009). Heat-wave induced mortality of food source species, ecological keystone species, and disease vectors and reservoirs are other examples of primary effects.

Indirect

Indirect health impacts arise as downstream effects of climate change and variability. These impacts are broad and variable in their etiology, such as change in infectious disease vector distribution and air pollution interacting with heat waves.

The changing ecology of disease-bearing vectors was raised by Leaf in 1989, though the health impacts of climate change on vector-borne diseases has been contested by some ecologists (e.g. Lafferty 2009) and experts from within the disease community (e.g. Gething et al. 2010; Randolph 2009). The debate is finally showing signs of abatement for some of the most prevalent vector-borne diseases, including malaria. Consensus is emerging that, indeed, climate change does magnify such risks (Siraj et

[7] Several plausible reasons have been put forth to explain their lack of prominence – the most likely being the interdisciplinary nature of these issues in the context of a scientific community that is still poorly equipped to equitably hear, consolidate and incorporate numerous competing interests, including those of social scientists (Castree et al. 2014; Heller and Zavaleta 2009). Thus, recent scientific culture has been reluctant to venture beyond a fairly narrow band of thinking, effectively tabooing integrative cross-sectoral analysis and written reflection on challenges such as differences in economic, political, cultural and other forms of power, population growth, the "right" to unbridled consumption and limits to growth and corresponding impacts on health, biodiversity and life-sustaining ecosystem services.

al. 2014), though advances in technology, prevention and treatment can combine to reduce the burden of diseases like malaria (Feachem et al. 2010). Climate change directly contributes to damage of both infrastructure and human settlements, resulting in human mortality and morbidity that includes the mental health and well-being of survivors (IPCC 2014d). In countries at all stages of development, these impacts are consistent with a lack of preparedness for climatic variability in some sectors; the most salient manifestations will be among the poorest and most vulnerable populations (IPCC, 2014d).

Tertiary

The third – "tertiary impacts" – category is, by a number of magnitudes, the most important health risk associated with climate change (Butler 2014b). These include the health impacts of large-scale famine, forced migration and human conflict, which result from the geophysical and ecological consequences of climate change, including the alteration of ecosystems, sea-level rise, and long-term disruptions in water supply and food production. Surprisingly, with rare exceptions, this group of effects has been little mentioned in the intervening decades, including in the most recent IPCC reports released in 2014.[7] These must be considered more holistically as we prepare to embark upon new global commitments on climate change and a post-2015 Development Agenda.

Many authors in this volume point to numerous synergies ("co-benefits") that could flow to both human well-being and ecological "health" from a more biosensitive approach to our relationship with nature (Boyden 2004), such as the co-benefits of cycling on both health and environment. Awareness of these co-benefits may also accelerate global social transformation (Haines et al. 2009; Raskin et al. 2002). On the other hand, many forms of inertia: social, institutional, technological and perhaps, above all, climatological, slow and impede the likelihood of a successful transition, most notably an enormous countermovement, funded and fuelled by vested interests profiting from "environmental brinkmanship" (Butler 2000). Delay is also worsened by the scientific knowledge gaps of many economists and policy-makers, who have been very slow to awaken to the risks we face, and who are instead wedded to more conservative or sectoral measures of progress, or to the hope that technological innovation alone will eventually solve the problem.

1.2 Vulnerability of biodiversity to impacts of climate change

The earth's biota was shaped by fluctuating Pleistocene concentrations of atmospheric carbon dioxide, temperature and precipitation; it has undergone multiple evolutionary changes and adopted natural adaptive strategies. Until the advent of industrialization, changes in climate occurred over an extended period of time, in a landscape much less degraded and fragmented than today, and with considerably less – if any – pressure from anthropogenic activity. Habitat fragmentation has confined many species to relatively small areas within their previous ranges, resulting in reduced genetic variability (Parmesan and Matthews 2006) and other changes to structure and composition (CBD 2009). Warming beyond the highest temperatures reached during the Pleistocene will continue to stress biodiversity and ecosystems far beyond the levels imposed by the climatic changes that occurred in the evolutionary past (Templeton et al. 1990; Parmesan 2006).

The impacts of climate change on biodiversity operate at different levels (including microbial, individual, population, species, community, ecosystem and biome), with variable responses at each level (Bellard et al. 2012; Parmesan and Martens 2009). For example, increased temperatures coupled with decreases in the distribution of precipitation may reduce freshwater levels in lakes and rivers (Campbell et al. 2009). Warmer temperatures cause fish populations to redistribute towards the poles, and tropical oceans to become relatively less diverse (CBD 2010). In other systems, drought may cause some tree species to disappear and in turn also fundamentally affect both vegetation structure and species composition (February et al. 2007).

Models of future biome distributions in tropical South America have found that substantial shifts in the region may lead to the substitution of Amazonian forest cover by savannah-like vegetation (Salazar et al. 2007; Lapola et al. 2009). The interaction between climate change, deforestation and fire can also lead to widespread forest dieback, with some parts moving into a self-perpetuating cycle of more frequent fires and intense droughts. At the same time, more frequent and powerful forest fires can compromise both the productivity of forests and their ability to store carbon (Barlow and Peres 2008; Bush et al. 2008). These combined impacts often lead to a reduction in regional rainfall, compromising agricultural production, livelihoods and food security (CBD 2010). Other models examining changes in natural vegetation structure and function in response to climate change predict that changes in vegetation cover in the tropics,[8] particularly in portions of West and southern Africa and South America, also include forest dieback (Alo and Wang 2008; Barlow and Peres 2008). Continued warming trends in oceans will accompany acidification as a result of increased carbon emissions, resulting in widespread degradation of tropical coral reefs[9] (Doney et al. 2009; Carpenter et al. 2008; Hoegh-Guldberg et al. 2007; Orr et al. 2005), and affecting the genetic and species diversity and composition of marine species such as molluscs, with corresponding impacts on our own sources of food, medicines, recreation and transportation (Bellard et al. 2012). Pollution is another pressure interacting with climate change (Seinfeld and Pandis 2012), and causing disruption to aquatic (Schiedek et al. 2007), terrestrial (Cramer et al. 2001) and marine ecosystems (Harvey et al. 2006).

It is difficult to analytically separate the influence of each of these drivers, as anthropogenic climate change and its effects are intimately dependent on interactions with other pressures such as land-use change and attendant habitat loss, and changes in water use, which themselves feed back into the hydroclimatic cycle (Elmhagen et al. 2015). These interactions in turn influence the ability of natural systems to respond at various spatial and temporal scales (Campbell et al. 2009). Further research on the complex interactions between these variables is critical, and we must also consider the underlying socioeconomic and other drivers of land-use change at multiple scales (Elmhagen et al. 2015; Lambin et al. 2001; Myers et al. 2013), and integrate input from a larger number of disciplines.[10]

An abundant number of predictive scenarios have shown no signs of abatement without the implementation of additional measures, including robust climate mitigation and adaptation strategies (e.g. IPCC 2014; CBD 2014). Alarmingly, some recent studies suggest that the impact of climate change on biodiversity has been estimated to have surpassed that attributed to land-use change and habitat loss (Selwood et al. 2014). As scientific research on individual drivers continues to proliferate, the impact of simultaneous multiple drivers, such as climatic changes driven by human water use for both food and energy production, remains a critical area for further research (Bellard et al. 2012; Destouni et al. 2013; Elmhagen et al. 2015).

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[8] It should be noted that simulated biosphere responses are model-dependent.

[9] Tropical coral reefs and amphibians have already been among the most negatively affected global biota, and range-restricted species, most notably polar and mountaintop species, have already led to species extinctions (Parmesan 2006). Current rates and magnitude of species extinctions (terrestrial, freshwater and marine) far exceed normal background rates, with increases of up to 1000 times that of historical background rates (MA 2005).

[10] For example, Lambin et al. (2001) suggest that land-use change is driven by both *proximate* causes (which are local and direct, and explain how and why anthropogenic activity acts on land cover and on ecosystem processes at a local scale), and *underlying* causes (indirect or root causes based on regional and sometimes global policies, economic forces and technological advancement that interact with and mediate the relationship at the local scale). The complex interactions between proximate and underlying causes interact over time (in a limited number of ways) to drive land management decisions and practices.

2. Climate change challenges at the intersection of biodiversity and human health

Climate change and variability have irreversible impacts on the global environment by altering hydrological systems and freshwater supplies, advancing land degradation and loss of biodiversity, and debilitating food production systems and ecosystem services, thus affecting health outcomes (WHO 2005). These factors are closely interrelated, as deforestation, industrial agriculture and centralized livestock production systems further accelerate climate change and biodiversity loss, thus contributing potential risks to food security, nutrition, and other aspects of health, livelihoods and well-being.

The IPCC has identified key risks across sectors and regions including, among others: (i) risk of loss of biodiversity of marine and coastal ecosystems, the goods and services they provide for coastal livelihoods, especially for fishing communities in the tropics and the Arctic, challenging sustained fisheries and aquaculture; (ii) risk of loss of terrestrial and inland water ecosystems, biodiversity, and the ecosystem goods, functions and services they provide for livelihoods; and (iii) risk of food insecurity and the breakdown of food systems linked to warming, drought, flooding, and precipitation variability and extremes, particularly for poorer populations (Field et al. 2014). In addition, rising CO_2 levels over the next century is likely to affect food nutritional quality, including the decrease of protein concentration and other nutrients of many human plant foods (Taub 2008; Fernando 2012; Myers 2014). Ocean acidification due to increased CO_2 concentration poses substantial risks to marine ecosystems, especially polar ecosystems and the biodiversity of coral reefs, thus challenging invertebrate fisheries and aquaculture (Portner et al 2014). Reductions in marine biodiversity due to climate change and ocean acidification might reduce the discovery of marine genetic resources useful in the pharmaceutical, aquaculture and other industries (Arrieta et al. 2010).

Climate-driven shifts in species distribution, abundance, seasonal cycles, desynchronized timing of life history events and ecosystem disruptions caused by extreme weather events have profound potential to disrupt and erode ecosystem services, release pathogens from previous constraints, and leave human populations ill-equipped to deal with compounding health challenges. However, studies of human health as a complex social–ecological system, replete with climate vulnerability, are relatively recent (McMichael and Wilcox 2009). Figure 1 shows the complexity of the nexus between climate, biodiversity and social interactions. Resilient or vulnerable communities may cope better, or worse, with both climate and biodiversity changes. Although building resilient communities is essential, in particular, given existing pressures on climate and ecosystems, the most efficient response is to jointly halt carbon emissions and ecosystem destruction.

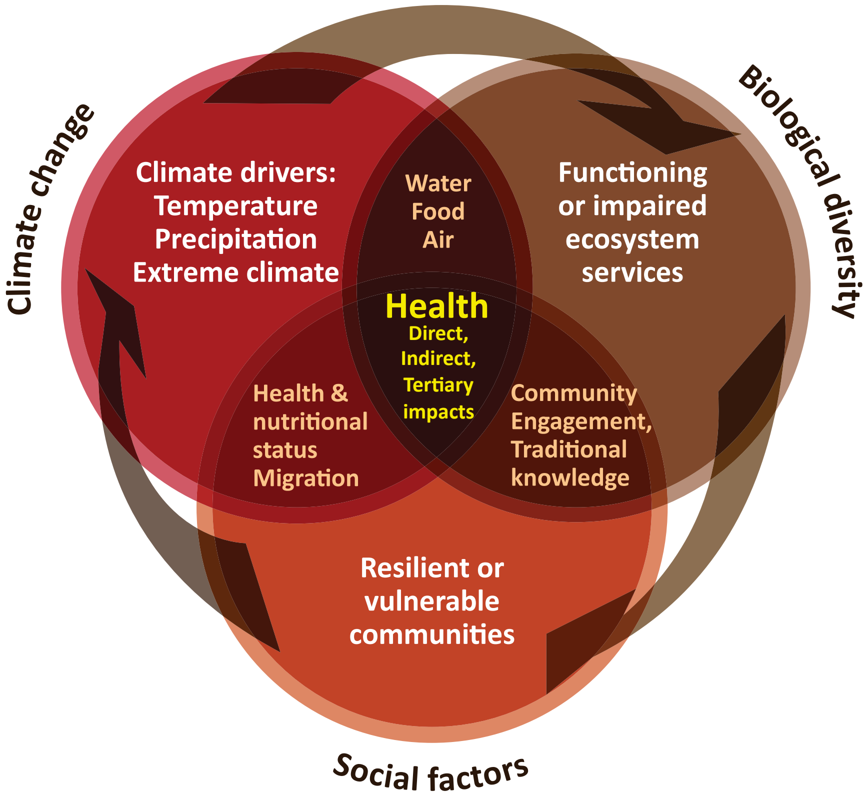
Attributing causality is complex (Parmesan et al. 2011; Parmesan and Yohe 2003) and presents a challenge to meta-analyses and the translation of scientific research into simple strategies for health or conservation agencies. Despite this challenge, observation and predictive studies of the direct, indirect and cumulative effects of climate change on human health acting through multiple levels of biodiversity are increasing. This body of information is guiding surveillance and further targeted research.

The breadth of interest in addressing climate change within the context of interlinked human, animal and ecosystem health at a global scale is discussed in the subsections below. We can identify several complex relationships with the primary, secondary and tertiary effects introduced in Box 1.

2.1 Climate change, food security and nutrition

The combined risks noted in the preceding section and in the chapters on agricultural biodiversity and nutrition constitute a challenge for food security and nutrition. This is particularly the case for the least developed countries and most vulnerable

FIGURE 1: Interactions between climate, biodiversity and social factors. Health is at the centre, in the intersection of these three drivers. The arrows are not causal but an expression of the dynamics inherent in the drivers. Social factors may be protective or harmful to health and well-being; climate drivers impact on biodiversity, on the social factors and directly or indirectly on health. Changes in biodiversity and ecosystems interact synergistically with climate change and are influenced by social factors. These feedback loops may magnify biological change and they sometimes exacerbate negative human health outcomes, directly or indirectly.



communities, such as indigenous populations, subsistence farmers and gatherers, pastoralists, coastal populations and artisanal fisherfolk (FAO 2008; Tirado et al. 2010). According to the IPCC, the risks of global aggregate impacts are moderate for additional warming between 1°C and 2°C, reflecting impacts to both the earth's biodiversity and the overall global economy. However, extensive biodiversity loss with associated loss of ecosystem goods and services results in high risks at around 3°C additional warming (Field et al. 2014).

Major climate impacts on water availability and food security affect disproportionately the welfare of the poor, including indigenous populations, women and girls, female-headed households and those with limited access to land, modern agricultural inputs, infrastructure and education (Field 2014). Indigenous peoples rely on their natural resources for the provision of traditional foods, fuel and medicines, and will be particularly affected by the impacts of climate on ecosystems, biodiversity and the environment (FAO 2008; Tirado et al. 2010). Traditional food systems are further threatened because of increasing loss of indigenous peoples' traditional territories due to climate change mitigation measures such as carbon sinks and renewable energy projects (FAO 2008). The demand for biofuel is likely to remain high, and this may result in the clearing of biodiverse land, such as tropical forests and wetlands, for the purpose of biofuel cultivation (Tirado et. al 2010).

In this context, it is essential to look for the co-benefits of nutrition-sensitive climate adaptation and mitigation strategies (Tirado et al. 2013). Across varying global landscapes, the ability for family farms, integrated agroforestry and farming systems to conserve, restore or augment biodiversity (e.g. species, genetic and ecosystem diversity) offer opportunities to enhance dietary diversity and nutrition, and promote climate resilience, especially as considered within broader social, economic and environmental policy frameworks. Adaptation measures targeting biodiversity (and ecosystem diversity) can simultaneously provide nutrient-rich food, and benefit the environment through supporting services such as pollination, nutrient cycling, temperature and water regulation, soil formation and pest control (CBD 2010).

2.2 Climate change and water security

As the chapter on freshwater and agricultural biodiversity in this volume describes, the provision of clean water for drinking, sanitation and agricultural uses is both an essential service regulated by ecosystems and an important health determinant (WHO 2012). While the long-term impacts of climate change on water resources are difficult to quantify, it is well established that human communities are reliant on groundwater for drinking, sanitation and other uses essential to human survival; yet rising sea levels cause saline water intrusion into essential groundwater aquifers near coastal regions, decreasing the availability of water resources for human purposes (Vörösmarty et al. 2000). Climate change contributes to more intermittent and intense precipitation patterns, increases the risks of floods, droughts and other hazards, causes the melting of glaciers and increases evapotranspiration rates, amplifies existing global public health challenges, and further destabilizes the balance of environmental and social systems (WHO 2012).

Variations in the hydrological cycle resulting from climate change must be closely monitored (Vörösmarty et al. 2000), together with the physical, biological and chemical processes that drive them at multiple levels, with consideration for the socioeconomic and political contexts of our human-dominated earth system (Bogardi et al. 2012). In this context, effective responses will necessitate innovative cross-sectoral initiatives and integrative climate adaptation and mitigation strategies, such as ecosystem based-adaptation (e.g. see Box 3).

2.3 Climate change impacts on traditional medicines, pharmacology and toxicology

Diversity in the production of secondary chemical products remains an important source of existing and new metabolites of pharmacological interest in medicinal plants, and this may be affected by climate change (Ziska et al 2009). Few studies have examined how pharmacological compounds might respond to recent or projected changes in CO_2 and/or temperature. For example, increases in growth temperature and CO_2 affect the production and concentration of atropine and scopolamine in jimson weed (*Datura stromonium*) (Ziska et al. 2005), and recent and projected CO_2 concentrations increase the production of morphine in wild poppy (*Papaver setigerum*) (Ziska et al. 2008).

More than 700 plant species are poisonous to humans. Rising temperatures and longer growing seasons would in principle increase the presence of such species in the environment, but the interaction between CO_2 and on the concentration or production of such poisons and plant toxicology is largely unknown (Ziska 2015) and needs to be explored. More than 100 different plant species are associated with contact dermatitis, which occurs by contact with plant chemical irritants present in leaves, flowers, savia roots, etc. One well-known chemical is urushiol that induces contact dermatitis in the poison ivy group (*Toxicodendron/Rhus* spp.). Poison ivy growth and urushiol congeners are highly sensitive to rising CO_2 levels (Mohan et al. 2006). These results suggest possible links among rising CO_2, plant biology and increased contact dermatitis. This area deserves further research.

2.4 Climate change and infectious disease emergence and re-emergence

The complex interactions between ecological factors and climate change increasingly predict changes in the global epidemiology of many vector-borne and waterborne diseases (WHO 2012). This is of growing interest and concern for scientists from a variety of fields, including ecology, microbiology, epidemiology and related medical fields (Lipp et al. 2002). Additionally, interest is garnered from experts in the social sciences, aware of the close relationship between the geophysical environment and the economic and social systems it sustains. Such interest emerges from concerns over human and animal health problems vulnerable to the interaction between climate change and other factors, such as increasing antibiotic resistance (Patz et al. 2005; Epstein 2001), emerging infectious diseases (Jones et al. 2008; Wilson 1991), and potential vulnerabilities of medicinal and aromatic plant (MAP) species.[11] These, in turn, have subsequent influence on the cultural and socioeconomic determinants of health (Cavaliere 2009; Padulosi et al. 2011).

There is mounting evidence that climate change will alter the patterns of animal (Altizer et al. 2013; Harvell et al. 2002), plant (Pautasso et al. 2012) and human (Patz et al. 2005; Purse et al. 2005) diseases. Additional evidence suggests that rising temperatures and changing humidity and rainfall patterns have already altered the distribution of some waterborne illnesses and disease vectors (IPCC 2014d), notably affecting populations with little or no acquired resistance and, as such, causing health systems to be destabilized (WHO 2012). For example, as the chapter on water quality indicates, cholera (causative agents *Vibrio cholerae* O1 and *Vibrio cholerae* 0139) remains a major public health problem, with ongoing outbreaks occurring in low-income countries with poor access to sanitation infrastructure[12] (Ali et al. 2012). Rising ocean temperatures affect the ecology of the aquatic environment, for example, by increasing algal blooms, with corresponding implications for the epidemiology of diseases such as cholera. The population dynamics of this pathogenic microorganism in the environment is strongly influenced by environmental factors such as salinity, seasonal patterns and the presence of copepods,[13] which in turn are modulated by larger-scale changes in climate (Lipp et al. 2002; Vineis et al. 2011). Prolonged floods and droughts may also contribute to water contamination and potentially exacerbate the risks of cholera and other forms of diarrhoeal disease (WHO 2012).

In natural systems, changing climatic variables can fundamentally influence successional processes and community dynamics. For example, a 12-year warming experiment in Colorado, USA, to evaluate the damage of pathogens and herbivores on six of the most common plant species (i.e. *Artemisia tridentata, Helianthella quinquenervis, Erigeron speciosus, Potentilla gracilis, Potentilla hippiana* and *Lathyrus leucanthus*) found that plants exposed to warmer temperatures suffered the most damage and were attacked by a larger number of species. The study concluded that climatic changes are likely to result in changes to community composition (Roy et al. 2004). Although there are few long-term datasets (for examples, see Jeger and Pautasso 2008; Fabre et al. 2011), a large number of other scientific analyses and modelling projects have been carried out to examine the impacts of climate change on plant pathogens and many have reached similar conclusions (see Pautasso et al. 2012 and references therein).

[11] Whether climate change poses a more prominent threat to MAP species than other threats such as unsustainable use is not established. However, the potential effects on MAPs may be particularly significant due to their cultural and medical value within traditional medicine systems (Cavaliere 2009). Moreover, given that many wild species, including MAPs, grow in mountainous regions, it is likely that at least some will be at risk (Padulosi et al. 2014).

[12] According to recent WHO estimates, only 5–10% of the actual number of cholera cases occurring worldwide are reported, and of the estimated 3–5 million cases that occur globally every year, about 100 000 to 120 000 people die (Ali et al. 2012).

[13] The causative agents of cholera include brackish waters (Tamplin et al. 1990) and crustacean copepods (Huq et al. 1983), and climate change contributes to an increase in both.

Box 2 discusses the impact of heat waves and other extreme weather events on fruit bats and bat-borne diseases. Loss of host predators and competitors, changes in parasite and pathogen survival and reproduction are additional mechanisms by which climate change impacts infectious disease. For malaria, disease transmission-enhancing changes have been described in the population dynamics of both the mosquito vector, and the pathogen within it, including altitudinal and latitudinal range shifts in Africa and South America (Siraj et al. 2014). While for many human diseases the potential effects of climate change are obscured by socioeconomic factors and control efforts, strong evidence of climate effects on infectious disease comes from invertebrate, animal and plant diseases (Altizer et al. 2013).

Box 2. Bat-borne diseases, climate, heat waves and extreme weather events: mounting evidence of important relationships

Bats, and fruit bats in particular, became the focus of increased human health interest after novel diseases, including Nipah virus disease and SARS, emerged in the 1990s–2000s. Land-use change and bush meat hunting are the suspected primary reasons for shifts in host and pathogen relationships (Luis et al. 2013) but the impact of climate is likely to be an additional factor in their emergence and continued transmission, as these species are capable of flying long distances to optimize resources and find alternative roosts. Widespread bushfires in Sumatra were suspected of influencing fruit bat–pathogen dynamics prior to the emergence of Nipah virus in Malaysia in 1998 (Chua 2003). While epidemic enhancement and agricultural intensification are co-factors (Pulliam et al. 2012), it remains possible that the fires and other climatic stress factors on food resources have influenced viral loads and spillover (Daszak et al. 2013).

More speculatively, climate change, together with deforestation and other land-use changes, has been hypothesized as a contributing factor in the recent outbreak of Ebola virus in West Africa (see also the chapter on infectious diseases in this volume). It is difficult to isolate climate as a driver in the context of extensive deforestation and profound economic and public health failures, further undermined by years of civil conflict (Bausch and Schwarz 2014). However, prolonged depression of primary forest production during lengthy droughts in central Africa followed by sudden rainfall events appears to enhance the opportunity for Ebola transmission between bats and other wildlife that concentrate on available resources (Tucker et al. 2002).

During the Australian summer of 2014, an estimated 100 000 fruit bats fell dead in the streets of Brisbane and south-eastern Queensland towns. (The number that died outside urban areas is unknown.) The bats are highly temperature sensitive (Welbergen et al. 2008) and it is unlikely they could survive a heat wave with temperatures above 43°C. Removing corpses was a major exercise for the urban authorities, and gloves and collection bins were supplied to residents. At least 16 people were treated for possible Australian bat lyssavirus (related to rabies and fatal without immunoglobulins) after they were scratched or bitten by dying bats. It is yet to be understood what effect the deaths will have on the bat colonies themselves. The 2011 spike and dispersed distribution of another zoonotic (transmissible to humans) Australian bat-borne disease, Hendra virus, is believed to be a consequence of the dispersal of bats after widespread flooding in south-east Queensland following Cyclone Yasi in 2010. The higher latitude range extension of two host species of this disease, and increased urbanization of all four, in preceding decades are suspected factors in disease emergence (Plowright et al. 2011).

2.5 Climate change and disaster risk reduction

Based on recent data from the United Nations International Strategy for Disaster Reduction (UNISDR), well over 80% of disasters are related to climate, contribute enormously to economic losses and, as the chapter on disaster risk reduction in this volume also indicates, trigger short- and long-term population displacement.[14] The impact of climate change on the frequency and intensity of extreme weather events, such as extreme precipitation, coastal flooding and heat waves, is already exacerbating risks to unique and threatened ecosystems, costing human lives and decreasing the viability of human settlements. In the last decade of the twentieth century, extreme weather events accounted for the death of some 600 000 people and caused damages worth billions of dollars (Hales et al. 2003). Based on the most recent findings of Working Group II of the IPCC, the risks posed by some extreme events, such as heat waves, are likely to be enhanced with only 1°C of additional warming. A large number of species and systems with limited adaptive capacities, including Artic sea ice and coral reef systems, are considerably threatened by a warming climate and, from a human perspective, many cultures are already at risk. The distribution of impacts from extreme weather events is uneven, with disadvantaged and vulnerable populations in countries at all levels of development being at greatest risk (IPCC 2014d).

Rising sea levels caused by the warming of the ocean, glacial melt and wetlands alteration (e.g. Syvitski et al. 2009) can cause increased flooding and the erosion and inundation of coastal ecosystems, further endangering wetlands and posing concomitant threats to coastal communities, including those of small island developing states (SIDS).[15] Without a significant scaling up of climate adaptation efforts, it has been projected that the rise in sea levels could increase the number of people exposed to coastal flooding more than tenfold by 2080 (a rise of more than 100 million people a year) (CBD 2010). Rising seas could also impact on human health and well-being through an increase in salination of coastal freshwater aquifers, and by disrupting storm water drainage and sewage disposal (Patz 2001). In turn, repeated flooding or increased salination can lead to population displacement, thereby further heightening the vulnerability of populations (Costello et al. 2009). As several case studies in the chapter on disaster risk have shown, refugees suffer substantial health burdens, overcrowding, lack of shelter and competition for resources, which is also often associated with conflict (WHO 2012).

The United Nations (UN) World Conference on Disaster Risk Reduction recently adopted the Sendai Framework for Disaster Risk Reduction 2015–2030, recognizing the intimate links between disaster risk, climate change and poverty. The confluence of these conditions lead to a convergence of less resilient built, natural and human environments, making populations more vulnerable to displacement, disease and the loss of livelihoods. To meet the resulting ambitious global targets, as well as those that may emerge from other global frameworks in 2015 – including under the UN Framework Convention on Climate Change (UNFCCC) process on climate change and in the UN post-2015 Development Agenda – each of the sectors must meaningfully engage, together with political authorities, local communities, civil society, and the public at large to understand and address the combined risks of poverty, land-use change, ecosystem degradation, climate change and poor urban planning.

[14] See http://www.unisdr.org/archive/42862 from 6 March 2015.

[15] The recently concluded "SAMOA Pathway" that emerged from the third UN Conference on Small Island Developing States held in September 2014 highlights the importance of a range of issues at the nexus of biodiversity, health and development, including climate change, in the context of particular threats faced by SIDS. See for example: http://www.sids2014.org/index.php?menu=1537.

2.5.1 Mountain ecosystems and climate change: at the intersection of water and food security, disease emergence, and extreme weather events

Mountain ecosystems are critically important centres of biodiversity. They play a unique role in the supply of services essential to human survival, especially critical to mountain dwellers and lowland communities. Occupying approximately one fifth of the land's surface, mountains play a critical role in the water cycle both by capturing moisture from air masses and as water sources[16] stored as snow, ice and permafrost, which provide fresh water to sustain communities, agriculture, energy production (primarily hydroelectric power), downstream industries and livelihoods (Price 1998). The large majority of the planet's major rivers and tributaries depend on water that begins the terrestrial phase of its cycle in mountain regions (Bajracharya and Shrestha 2011; Bandyopadhyay et al. 1997; MA 2005; CBD 2012). In arid and semi-arid regions, over 90% of river flow is derived from mountains (Price, 1998).

Mountain ecosystems are particularly vulnerable to the impacts of climate change, with corresponding impacts on the populations reliant upon the critical resources and services they provide, including water, energy, timber and food (see Box 3).

Box 3. Climate change and ecosystem-based adaptation in the Hindu Kush Himalayas[17]

The Hindu Kush Himalayas (HKH), otherwise referred to as the greater Himalayan region, extend from eastern Nepal and Bhutan to northern Afghanistan, and have among the most extensive areas covered by glaciers and permafrost on the planet. They contain water resources that drain through ten of the largest rivers in Asia,[18] from which over 1.3 million people derive their livelihoods and upon which many more depend for water and other resources (Eriksson et al. 2009). The region has been recognized as a uniquely biodiversity-rich area with equally unique topographic characteristics and socioeconomic and environmental challenges. The accelerated rate of warming,[19] glacier ice melt and related implications on the hydrological systems of central, south and east Asia are among the most widely cited (Armstrong 2010; Eriksson et al. 2009). The retreating of glaciers (in this region and elsewhere) is a sentinel indicator of climate change but also one of the most difficult to quantify, given the physical and spatial complexity of glaciers and data collection.[20]

Ongoing challenges in regions in which large proportions of the population live in mountain communities, such as Bhutan and Nepal, include poverty, poor medical support, less access to education and shorter life expectancies. While climate change may bring some benefits to mountain

[16] In the greater Himalaya region, it is estimated that snow and glacial melting contribute approximately 50% of annual river flows (Eriksson et al. 2009).

[17] Here, the term Hindu Kush Himalayan (HKH) sometimes referred to as greater Himalayan region, includes the Himalayan, Hindu Kush, Karakoram, Pamir and Tien Shan mountain ranges, where there is currently glacier coverage. The HKH, however, does not constitute one single region, as the eastern Himalayas are separated from the Karakoram–Hindu Kush mountains by approximately 2000 km, though there is no sharp separation between east and west. Differences in climate and in glacier behaviour and dynamics have been reported across the area, with variations in these conditions throughout (Armstrong 2010).

[18] These are the Amu Darya, Brahmaputra, Ganges, Indus, Irrawaddy, Mekong, Salween, Tarim, Yangtze and Yellow Rivers.

[19] It has been estimated that global warming in the region has been 0.6 °C per decade versus 0.74 °C per hundred years as a global average (Eriksson et al. 2009).

[20] Several glaciers in the extended HKH region are retreating but the extent of the impact of climate change on glacier ice is not well known as glacier data in the Himalayas and surrounding mountains are very sparse and conditions vary significantly along the south–east to north–west transect of the Himalayan–Karakoram–Hindu Kush mountain ranges (Armstrong 2010).

regions (e.g. longer growing seasons), mountain dwellers and lowland communities also face a broad and unique range of climate-related health risks. These include water and food shortages, increased risk of natural disasters and the expansion of water-related and vector-borne diseases (Ebi et al. 2007; Ahmed and Suphachalasai 2014).[21] Increased variability in precipitation patterns (including variability in monsoon and more frequent extreme rainfall), coupled with increased risk of extreme weather events and glacial ice melt are predicted to increase the risk of floods (carrying rock, sediments and debris), landslides, threats to forest ecoregions including increased forest fires in some areas, soil erosion, and habitat and ecosystem disruption,[22] damage to infrastructure and property, injury and loss of human life (Ahmed and Suphachalasai 2014; Armstrong 2010; Ebi et al. 2007). Of particular concern in the region are the potentially devastating impacts on mountain dwellers and lowland communities from glacial lake outburst floods, which have become more frequent since the latter half of the twentieth century (WHO 2005; Armstrong 2010).

Addressing the threats posed or compounded by climate change demands the development of integrated and holistic approaches for the management of mountain ecosystems that sustain the flow of life-supporting services. This can be achieved with innovative adaptation solutions (including ecosystem-based adaptation), such as sustaining highland wetland systems that provide water regulation, other services and habitats for critical animal and plant species (including medicinal plants), or new technologies such as drip irrigation systems (CBD 2012; Chettri 2011).

Ecosystem-based adaptation in fragile mountain ecosystems such as HKH can not only provide co-benefits at the global or national level but may also be integrated into regional policies to jointly encourage climate change adaptation, biodiversity conservation and sustainable use, and development at a landscape level (Sharma et al. 2010). In the HKH, holistic ecosystem-based adaptation strategies that emphasize adaptation as an interdisciplinary issue have been advocated. These interventions seek to achieve the sustainable management of the transboundary reserve system through the application of landscape-based solutions to jointly reduce the vulnerabilities of biodiversity and local communities to climate change and other drivers by restoring endemic vegetation, developing connectivity between ecosystems, and monitoring large-scale changes to increase the social and economic resilience of local populations (Chattra et al. 2009).

2.6 Climate change and urbanization

The global urban transition provides challenges and opportunities for health at the intersection of climate change and biodiversity. Currently, urban populations are growing by more than 1 million people every week and, by 2030, it is estimated that 2 in every 3 people will live in urban areas – a total of more than 6 billion urban dwellers worldwide. Most future population growth will be in small- and medium-sized cities in low- and middle-income countries. Urban health inequalities are well documented (WHO and UN-HABITAT 2010), and rapid, unplanned urbanization threatens biodiversity and exacerbates public health challenges across different levels of economic development. Climate change especially amplifies health risks among

[21] For example, the reduced availability and quality of freshwater or changes in monsoon patterns can at once affect agricultural production by decreasing crop yield, increasing water and food insecurity (particularly for those living at altitudes of 2500 m or higher) and lead to a rise in the prevalence of waterborne diseases such as diarrhoeal disease (Ebi et al. 2007). The impacts on agriculture and food production can also be especially severe. For example, in Nepal, an estimated 64% of all cultivated area is dependent on monsoon rainfall (Chaudhary and Aryal 2009).

[22] Some species may even become extinct as a result of gradual habitat loss resulting from global warming, particularly in mountain biota above the tree line, and in high latitude and high altitude biomes (Chaudhary and Aryal 2014; Chapin 2004).

poor and vulnerable communities, including through inundation in low-lying cities and the health risks from inadequate water supply, sanitation and housing. However, affluent urban areas also face new challenges. In addition to other negative health impacts described throughout this volume, recent findings suggest that climate change may contribute to an increased incidence in allergies, particularly in urban areas.

Climate change may alter the diversity, production, allergenicity, distribution and timing of airborne allergens. These changes contribute to the severity and prevalence of allergic disease in humans. Increased CO_2 and temperature is altering seasonality and beginning to affect the quantitative and/or qualitative aspects of the three distinct plant-based contributions to allergenic pollen: trees in the spring, grasses and weeds in the summer, and ragweed (*Ambrosia* spp.) in the fall (autumn) (Ziska et al. 2015). For example, a recent study on changes in climate in the United States has found that rising temperatures, altered precipitation patterns, and increasing atmospheric CO_2 are expected to contribute to increasing levels of some airborne allergens, and associated increases in asthma episodes and other allergic illnesses, compared to a future without climate change (Neal et al. 2015). Several prior studies using urban areas as proxies for both higher temperatures and CO_2 also showed earlier flowering of pollen species, which may lead to a longer total pollen season (Neil and Wu 2006; George et al. 2007). Microclimatic effects of urbanization have been associated with longer pollen seasons and earlier floral initiation in European cities (Rodriguez-Rajo et al. 2010). As climate change, biodiversity loss and other pressures combine to pose new challenges, they also present new opportunities for positive development to protecting biodiversity, health and well-being, including in urban areas and at subnational levels (Puppim de Oliveira et al. 2010). Further multidisciplinary study of these various intersections and greater collaboration across various scales of governance, including local governance and communities, are a necessary prerequisite to meeting these challenges (Reid 2015). As the next section discusses, ecosystem-based conservation and adaptation provide important opportunities for communities to play a central role in the development of strategies to address climate change.

3. Ways forward

3.1 Ecosystem-based adaptation and ecosystem-based mitigation

Biodiversity conservation can support efforts to reduce the negative effects of climate change through ecosystem-based approaches to mitigation and adaptation.[23] Conserved or restored habitats can remove CO_2 from the atmosphere, thus helping to address climate change by storing carbon (for example, reducing emissions from deforestation and forest degradation). Mangroves are natural sources of biodiverse food, fish, shells, fruits, fuel, medicines, and they act as natural bioshields that protect coastal lands and local communities from the impacts of climate-related extreme weather events, and also contribute to carbon sequestration. Adaptation strategies to conserve intact mangrove ecosystems or to repopulate them can thereby help attenuate potentially severe impacts of climate change, including flooding and storm surges, while contributing to climate mitigation efforts and saving human lives (Das and Vincent 2009).

Many successful examples of ecosystem-based approaches are beginning to emerge.[24] Ecosystem-based adaptation (EBA) activities can include: establishing diverse agroforestry systems to

[23] Ecosystem-based adaptation (EBA) integrates the use of biodiversity and ecosystem services into an overall climate change adaptation strategy, while ecosystem-based mitigation (EBM) involves using ecosystems for their carbon storage and sequestration abilities, by creating, restoring and sustainably managing ecosystems as a climate mitigation strategy.

[24] For example, the forest rehabilitation project in Krkonoše and Sumaya National Parks in the Czech Republic is one of several examples of the implementation of ecosystem-based adaptation strategies and the challenges they have encountered (see Naumann et al. 2011; Dowald and Osti 2011).

cope with increased risk from climate change;[25] sustainable management of upland wetlands and floodplains for maintenance of water flow and quality; conserving agrobiodiversity to provide specific gene pools for crop and livestock adaptation to climate change; maintaining or restoring mangroves or other coastal wetlands to reduce coastal flooding and erosion; and conservation and restoration of forests to stabilize land slopes and regulate water flows (Munang et al. 2013). EBA and ecosystem-based mitigation (EBM) strategies and approaches can additionally be highly cost–effective options that provide a range of social, economic and cultural co-benefits while proactively responding to the adverse impacts of climate change, safeguarding biodiversity and contributing to the livelihoods of local communities (CBD 2009; Doswald and Osti 2011; Goulden et al. 2009).

In Central and South America, there are several examples of EBM strategies that support the establishment of protected areas, conservation agreements and community resource management. Resilient crop varieties, climate forecasts and integrated management of water resources are also being adopted in the agricultural, aquaculture and silviculture sectors (IPCC 2014d). Aqua–silviculture systems, which integrate mangrove forestry with fish and crab aquaculture ponds, are commonly used in South-East Asia. These systems are more resilient to shocks and extreme events, and they also lead to increased production due to improved ecosystem services. While climate change adaptation is becoming embedded in some planning processes, the implementation of responses remains variable and requires strengthening (IPCC 2014d). EBM and EBA strategies that include communities as a central component of planning, address the governance and policy context within which they are developed, and build on interdisciplinary scientific inquiry, provide valuable opportunities to address these challenges, and to scale up these strategies through mainstreaming and diversification across sectors (Reid 2015).

4. Conclusion

A range of local (e.g. invasive species) and global (e.g. long-range pollution) stressors can make natural adaptation more difficult in the face of accelerating climate change. In the absence of robust climate mitigation and adaptation strategies, the rate and extent of anthropogenic activity contributing to climatic changes will continue to affect biodiversity, constrain the capacity of ecosystems to deliver essential services, and affect human health both directly and in combination with other drivers and pressures. These include land-use change, pollution, population growth, urbanization and globalization (Campbell et al. 2009; Parmesan and Martens 2009). These demand the adoption of a broad range of multilevel sustainable-use and conservation practices (e.g. strengthening protected area networks; ensuring adaptive management through monitoring and evaluation). The full involvement of communities and policy-makers alike is a key determinant of their success (Martínez et al. 2012). Additionally, climate change adaptation and mitigation strategies cannot be dissociated from health equity considerations, without which equity gaps are likely to increase with a resounding impact on the social determinants of health for the poorest, most vulnerable communities (Costello et al. 2009).

There is a reservoir of important indigenous traditional knowledge, which is an invaluable resource for climate change adaptation and biodiversity conservation in indigenous populations, and increases the effectiveness of adaptation planning strategies (Field et al. 2014; Bennett et al. 2014). Indicators of climate adaptation and resilience should also include nutrition outcomes such as the Dietary Diversity at the Household level (HDDS), including Women's Dietary Diversity Score (WDDS) or the new indicator Minimum Dietary Diversity for

[25] Forests provide a carbon reservoir as they contain about 60% of all carbon stored in terrestrial ecosystems (CIFOR 2007), and they can serve as important buffers for climate adaptation strategies. As deforestation contributes a large proportion of global carbon emissions, curbing deforestation and investing in reforestation activities are a critical adaptation strategy (Chaudhary and Aryal 2009).

Women (MDD-W), which has been suggested for consideration as one of the priority nutrition indicators for the post-2015 Sustainable Development Goals (SDGs).

Conserving natural terrestrial, freshwater and marine ecosystems and restoring degraded ecosystems (including their genetic and species diversity) are also essential for the overall goals of both the CBD and the UNFCCC. The key role of ecosystems in the global carbon cycle, for climate change adaptation, for the provision of a wide range of ecosystem services essential to human health and well-being, and for the broader goals of sustainable development, including the MDGs and SDGs that will follow (Haines et al. 2012), make an ecosystem approach indispensible. Since 2008, WHO has also adopted a very active programme to guard human health from the impacts of climate change[26] and it recently hosted its first international conference on related health issues.[27] While somewhat buffered against environmental changes by culture and technology, human health is fundamentally dependent on the continuing flow of ecosystem services (Corvalán et al. 2005).

Among poor and vulnerable populations in particular, climate change is already affecting health in myriad ways and, more generally, climate change presents increasing future health threats worldwide (McMichael et al. 2012). Climate change affects health through primary, secondary and tertiary mechanisms, including its impacts on biodiversity and ecosystem service provision (Butler 2014a), adding urgency to the task of addressing other international health priorities (Haines et al. 2012). The recognition that climate change mitigation strategies can have substantial benefits for both health and biodiversity conservation presents policy options that are potentially both more cost–effective and socially attractive than are those that address these priorities independently (Haines et al. 2009).

The magnitude and breadth of these impacts will require large-scale cross-sectoral efforts and integrative approaches to the analysis of environmental change and health outcomes. In turn, these must draw not from an isolated analysis of health impacts but also draw on historical and contemporary insights about the underlying "factors that have determined the structure and distribution of biodiverse systems" (Hoberg and Brooks 2015). Holistic strategies for climate change mitigation and adaptation, which jointly consider multiple objectives, including biodiversity conservation and livelihoods, will likely be more effective and sustainable than stand-alone strategies that focus on any single objective, such as carbon sequestration (Heller and Zavaleta 2009).

Looking ahead, global health leaders are now calling for a "planetary health" approach with strengthened focus on threats to human civilizations and, ultimately, human survival, from disturbances in planetary systems (Horton 2013; Lancet-Rockefeller Foundation Commission on Planetary Health 2015), and an ecosocial understanding of health, which acknowledges its ecological, economic and social foundations. There is a pressing need to formally recognize key environmental limits and processes, and the thresholds that we must respect in order to maintain the sustainability of our planet (CBD 2014; Rockström et al. 2009). The current reliance on gross domestic product (GDP) as the primary indicator of success has led to perverse outcomes and has not delivered fair levels of well-being for society or individuals (Fleurbaey and Blanchet 2013). Contraction and convergence will bring potential health benefits (Stott 2006). Accounting for benefits to health and well-being in development decision-making can encourage transitions to more sustainable and equitable patterns of resource use and consumption and, at the same time, improve population health (Dora et al. 2014). These changes are essential to avoid widespread and profound damage to ecosystems, upon which human survival ultimately depends.

[26] World Health Assembly resolution 61.19: Climate change and health. Geneva: World Health Organization; 2008. Available at: http://www.who.int/phe/news/wha/en/index.html.

[27] http://www.who.int/globalchange/mediacentre/events/climate-health-conference/en/

14. Increasing resilience and disaster risk reduction: the value of biodiversity and ecosystem approaches to resistance, resilience and relief

1. Introduction

Increasing evidence suggests that the frequency, nature and scale of (at least certain types of) natural disasters is changing: more mid- and small-sized disasters are now occurring more often, while increasing urbanization and the threat of climate change place more focus on the future social, economic, environmental and public health impacts of natural disaster events (ADW 2012; Guha-Sapir et al. 2013; Smith et al. 2014; Adger et al. 2014). Three of the top 10 risks in terms of impact over the next 10 years are identified as environmental risks – water crises, the failure of climate change adaptation and loss of biological diversity (Global Risks Perception Survey 2014).

The United Nations International Strategy for Disaster Reduction (UNISDR) defines a "disaster" as a serious disruption of the functioning of a community or a society, involving widespread human, material, economic or environmental losses and impacts, which exceeds the ability of the affected community or society to cope using its own resources (UNISDR 2009). Disaster events can be natural or anthropogenic in origin, or be triggered by a combination of these factors. Human-induced disasters can include conflict and pollution events, while natural disasters may be geophysical (earthquakes, landslides, avalanches, volcanic eruptions), climatic (hurricane, tsunami, flooding, drought, storm surge) or biological (epidemics, pest infestations). Combining these elements, anthropogenic activities – such as road construction, deforestation and mining – can cause or exacerbate natural disasters. The impact of these infrastructures, and ecosystem disturbance more broadly, may also pose immediate health risks, by contributing to disease emergence or food insecurity, or increasing vulnerability to mental health issues, for example.[1] These are referred to as "socionatural hazards", whereby human activities overexploit or degrade environmental resources, increasing the magnitude of disasters and/or the frequency with which they occur.

Disaster situations are associated with significant challenges for public health. The most immediate threat to health may be posed by the disaster event itself; for example, geophysical and extreme weather events can cause significant physical and mental trauma and loss of life (Guha Sapir et al. 2014; Du et al. 2010; Wisner et al. 2008), while epidemics are by their nature primarily a public health concern. Furthermore, disasters can exacerbate other public health risk factors, by altering the natural and physical environment, affecting critical infrastructure (e.g. associated with clean water and sanitation or primary health care), and changing human conditions (e.g. through

[1] For example, the impact of dams can significantly contribute to the emergence and spread of schistosomiasis, as described in the chapter on water quality.

displacement, injury, or loss of social and family support). In some circumstances, this can lead to an increased risk of infectious disease outbreaks (Watson et al. 2007; Kouadio et al. 2012). People affected by disasters – either through direct impact or perhaps indirectly through loss of employment or social disruption – are often vulnerable to psychological stress and related health conditions, including depression, anxiety and post-traumatic stress disorder (Neria et al. 2008). Where disaster events impact on food production systems or otherwise reduce the availability of basic foods, those affected may also be at risk for nutritional deficit (Weingärtner 2005; UN SCN 2002). The health burden of disasters is likely to increase as a result of climate change (Sena et al. 2014; Kein 2008).

Recognition of the widespread ecological and humanitarian impacts associated with human-induced disasters, including the aftermaths of conflict and land-use change, has highlighted the need for sustainable multistakeholder solutions (Hanson 2011; Guha-Sapir and D'aoust 2011; Leaning and Guha-Sapir 2013; Promper et al. 2014).

The changing nature of disasters is likely to result in greater loss of life, considerable economic costs, reduced livelihood opportunities and significant – possibly lasting – damage to critical ecosystems such as watersheds or coastal wetlands. However, while disasters can have a detrimental impact on biodiversity and may even result in the collapse of essential ecosystem services, diverse and well-managed environments can help reduce disaster risks and enhance community resilience to both natural and anthropogenic events.

Urban expansion and infrastructure development, increasing population pressures, unsustainable agricultural intensification and climate change, all of which can be significant drivers of biodiversity loss and ill-health, are increasing disaster risks for many communities. Rapid-onset, previously infrequent, high-impact disasters, for example, are now considered the norm, and many locations and communities are experiencing greater susceptibility to repeated and prolonged disaster events. More small- and medium-sized disasters are also occurring now and the cumulative effects of these on the assets – including biodiversity – and livelihoods of vulnerable populations may, in the long term, have the same effects as high-magnitude events. Understanding the nature of potential disasters is being increasingly recognized as necessary for informed decision-making. Biodiversity – particularly its role in underpinning ecosystem services – can play a crucial role in disaster risk management before, during and after an event by fostering *resistance*, building *resilience* and assisting *recovery*. Expanding on the need for more integrative approaches discussed throughout this volume, such as the ecosystem, Ecohealth, or One Health approach, this chapter describes an ecosystem-based approach to disaster risk reduction (discussed in detail below) and examines the ways in which ecosystem services can support the ability of communities to manage disaster risk in an integrated and sustainable manner. The three sections that follow expose the heterogeneity of disaster events and the responses of ecosystems to such events, drawing upon an ecosystem-based approach, with support from a number of relevant case studies.

1.1 Overview: resistance, resilience and recovery

In the academic literature related to disaster management, the terms "resistance" and "resilience" are often used interchangeably, although there are some important distinctions between them (Green 2008). While resistance refers to the ability of a system to avoid having a disaster impact in the first instance, disaster resilience pertains to the ability of a system to mitigate, recover from, or adjust to, a disaster. Resistance can therefore be thought of as a form of *proactive resilience*, denoting capacity to anticipate a disaster and act on this before it can materialize.

"Recovery" pertains to the restoration (and improvement, where appropriate) of facilities, infrastructure and livelihoods in disaster-affected communities *after* an event has occurred, often including rehabilitation and reconstruction (UNISDR 2009). For a holistic and sustainable disaster response, these activities should be integrated with development initiatives, combining tangible restoration projects with capacity building, awareness-raising and policy formulation (WCPT 2014).

The identification of standards and metrics for measuring disaster resilience is one of the many challenges faced by policy-makers. This concept has been examined by a broad range of research perspectives. Expanding on the key concepts described above, this chapter adopts a temporal perspective, examining the role of biodiversity and well-managed ecosystems in disaster risk reduction, and exploring the benefits these can offer before, during and after disaster events. This perspective has been adopted because – as described throughout this volume – the impacts of disasters on complex ecosystems and health can vary considerably through space and time. A socioecological dimension has also received considerable attention and it is worth noting that both resilience and vulnerability are also influenced by social characteristics (see, for example, Cutter et al. 2008). In coupled socioecological systems, the same drivers can result in both social (including health) and environmental inequities (e.g. Bunch 2011). Considering these dimensions is, therefore, critical to improving public health outcomes and reversing the drivers of negative ecosystem change. Section two describes the potential of ecosystem-based approaches to prevent disasters in their entirety, or to mitigate their effects should this not be possible. Section three adopts a slightly different approach and examines the *complexity* of the links between biodiversity and disasters, emphasizing the reciprocity of this relationship. While ecosystems can foster resistance, buffer the effects of disasters and assist with response and recovery, disasters can cause significant ecosystem degradation and biodiversity loss, which may catalyse or exacerbate the risks of further events. This is illustrated by the case study on refugees and internally displaced persons (IDPs) described in section 3.

2. Biodiversity and disaster risk reduction: prevention and mitigation

This section outlines the integral role of biodiversity in disaster management, with a specific focus on its ability to eliminate or lessen the impacts of certain events. Well-managed and healthy ecosystems represent an opportunity to reduce disaster risk, which eschews a total reliance on physical engineering structures, promoting integrated use of certain ecosystems with physical infrastructure, offering a sustainable and cost–effective way to reduce disaster exposure, magnitude and frequency. By conserving and restoring ecosystems, sustainable natural resource management has the potential to make a significant contribution to the prevention and mitigation of disasters, addressing existing and emerging risks to foster resistance and build resilience. At the same time, such an approach goes a long way towards ensuring that certain natural resources, including food and medicinal products – both known and not yet discovered – are potentially available for use by communities who depend on these as a traditional form of livelihood and food security.

The World Risk Report (2012) conceptualizes risk as an outcome of the interaction between the likelihood a disaster and the vulnerability of societies, with vulnerability comprising the abilities and capacities of people or systems to cope with and adapt to the negative impacts of disaster events, including health impacts. Thus, risk is defined as a product of disaster exposure and the susceptibility, coping capacities and adaptive capacities of a population. These population features are determined by the interplay of a range of physical, sociocultural, economic, political and environmental factors in a specific context, indicating the complexity of "risk" as a concept and its perpetual (trans)formation (ADW 2012).

Disaster risk reduction (DRR) is a systematic approach to identifying, assessing and reducing the risks of disaster events. Strategies aim to reduce the likelihood of disaster events, minimize vulnerabilities and prevent, mitigate and/or enhance preparedness towards the adverse impacts of disasters (UNISDR 2004).

Conventionally, attempts at DRR have focused on the protection of people and infrastructure through zoning and/or using "hard" engineering solutions, such as dams, levees and sea walls. As described in the chapter on water, these infrastructures are often expensive to build and operate, can generate unforeseen environmental and social consequences and – in many cases – have fallen short in the performance of their protective duties (ProAct 2008; Badola and Hussain 2005; Sudmeier-Rieux and Ash 2009). In light of this realization – and the changing nature of disaster events described above – a search for alternative means of reducing disaster risk has opened opportunities for increased attention to ecosystem-based management approaches.

The ecosystem-based approach to DRR recognizes and seeks to investigate and use the potential of biodiversity and ecosystem goods and services to support the ability of communities to reduce and adapt to risk in an integrated and sustainable manner. It has been described as one of the few approaches that can impact all elements of the disaster risk equation: reducing exposure and vulnerabilities, and increasing the resilience of exposed communities and their assets (PEDRR 2013).

Ecosystem engineering solutions – based on ecosystem services that use natural and/or managed ecosystems – comprise an integral component of ecosystem-based strategies and have become increasingly popular, particularly since the 2004 Indian ocean tsunami (ProAct 2008). This disaster, in particular, highlighted the potential protective capacities of coastal forests and brought mangrove rehabilitation and conservation to the forefront of the environmental agenda in South-East Asia (Giri et al. 2008). At the global scale, an increasing number of United Nations (UN) agencies and international nongovernmental organizations (INGOs) have since expanded their

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interest in ecosystem-based approaches to DRR and plan to further integrate these into their core activities in recognition of the "increasing importance of ecosystem management in adapting and responding to climate change impacts and associated disaster risks" (UNEP 2009; World Bank 2009).

In the international policy arena, the Hyogo Framework for Action (HFA) (2005–2015) also acknowledges the role of healthy ecosystems and sustainable environmental management in reducing disaster risks. Under its fourth Priority for Action – "reduce the underlying risk factors" – activities include the "appropriate management of fragile ecosystems" and "the sustainable use and management of ecosystems... to reduce risks and vulnerabilities". Unfortunately, efforts at ecosystem management for DRR have been largely made on an ad-hoc basis, and a mid-term review of the HFA determined that Priority Four has made the least progress of the five Priorities for Action (UNEP 2009b; van Eeden 2013; PEDRR 2013).

This is illustrative of a general difficulty encountered in the context of disaster management strategies, whereby there is often a disconnect between the intentions of government authorities, humanitarian and relief organizations, donors and civil society, and the emergence of practical and appropriate interventions in the field. Opportunities to adopt ecosystem-based adaptation (EbA) measures have not been taken and laudable de jure proclamations extolling the benefits of biodiversity and ecosystem services for sustainable DRR have not been translated into de facto actions, with concomitant implications for human security. EbA strategies that have been implemented have often been prone to failure, due typically to an absence of local participation, various financial and technical impediments, and the recurrent underutilization of scientific knowledge (Quarto 2012; Kathiresan 2008). Notwithstanding these challenges, a number of successful EbA DRR experiences in recent years attest to the potential of this approach to contribute to disaster prevention and mitigation, helping to build the resistance and resilience of human systems to existing, emerging and evolving risks.

2.1 Disaster prevention: the role of biodiversity in reducing the likelihood of disaster events

Disaster prevention expresses the concept of and intention to completely avoid potential adverse impacts through action taken *in advance* (UNISDR 2009). It is closely related to the concept of disaster *resistance*, which suggests the ability of a system to evade the onset of a disaster and its impacts, and to continue to function at close to normal capacity and capability.

Prevention has only recently become a permanent feature of modern disaster management frameworks – accompanying a general shift from reactive to proactive disaster responses. Examples include the construction of dams or embankments that reduce flood risks, and land-use regulations that prohibit settlement in high-risk zones. In terms of EbA for disaster prevention, ecosystems can also deliver benefits. For example, properly sited wetlands can reduce flood risks through water flow regulation, while certain mixtures of vegetation cover can – according to the specific site location and characteristics – help act as a form of ecological engineering, stabilizing steep slopes and preventing or reducing the scale of avalanches, soil erosion and gulley formation.

Although preventive measures are designed to provide permanent protection from disasters, it must be recognized that not all disasters can be prevented and, in many cases, their complete circumvention is unavoidable. Obviously, where a disaster may not always be prevented then once it occurs its impacts need to be mitigated. In the event of a tsunami or volcanic eruption, for example, disaster risk should be *mitigated* to the greatest extent possible.

2.2 Disaster mitigation: the role of biodiversity during a disaster event

"Mitigation" describes the alleviation or limitation of the adverse impacts of disasters. These impacts often cannot be prevented fully, but their scale or severity can be substantially lessened by various strategies and actions (UNISDR 2009).

Case study: The use of vegetation in slope stabilization

In China, artificial, human-made structures have traditionally been employed to protect communities and infrastructure from shallow landslides, but these have short lifespans and have in many instances caused considerable disruption to ecosystems. Ecological engineering involves "the design of sustainable ecosystems that integrate human society with its natural environment for the benefit of both" (Stokes et al. 2014). The use of plants as ecological engineers represents a more cost–effective and enduring option to combine with civil engineering approaches, with the potential of being self-sustaining, increasing in efficacy over time, enhancing local biodiversity, and providing a plethora of ecosystem services that can help address various drivers of livelihood vulnerability.

Several studies have shown that the establishment of certain types of vegetation cover significantly reduces shallow landslides and erosion on steep slopes (>35°) due to the ability of root systems to modify the biophysical, mechanical and hydrological properties of soil (Stokes et al. 2010; Reubens et al. 2007; Fattet et al. 2011; Ghestem et al. 2011; Mao et al. 2014). To be effective, however, ecological engineering techniques require that the mechanical, chemical and architectural traits of plant root systems be determined on a site-specific basis to determine optimum species combinations and planting configurations for rehabilitating, protecting and stabilizing degraded slopes (Stokes et al. 2014).

Certain species are traditionally favoured in slope stabilization – such as vetiver grass in China (Ke et al. 2003), but monocultures can be a high-risk venture, thus favouring a mixture of different plant functional types for slope stabilization, for example (Stokes et al., 2014; Fattet et al., 2011; Pohl et al. 2009; Reubens et al. 2007). Polyculture plantations provide a range of root systems for optimum soil stability. They also foster a heterogeneous environment for enhanced biodiversity and overall ecosystem functioning, as well as supporting opportunities for income generation and a number of other socioeconomic co-benefits (Gouzerh et al. 2013; Shi and Li 1999; Post and Kwon 2000; Cavaillé et al. 2013).

While ecological engineering usually does not incorporate, but can enhance the efficiency of, human-made structures, another key distinction between these approaches relates to their effectiveness over time and space. From the first moment of hard engineering installation, no erosion should occur; however, this ecological engineering relies largely on plant growth, leaving a window of susceptibility during the early years of restoration of a site when plants are too small to fully contribute to soil stability (Stokes et al. 2004; 2008).

Mitigation measures encompass, for example, engineering techniques, improved environmental policies and educational campaigns, and can be implemented at a range of scales. At the household level, awareness-raising schemes can encourage an avoidance of unnecessary risks through encouraging the preparation of emergency kits or the procurement of personal insurance. At a larger scale, the instalment of gas shut-off valves for earthquake events or the construction of houses on stilts to reduce flooding damage also comprise common mitigation efforts, while early warning systems may be established and building design standards integrated into policy at the national level.

Mitigation is linked to the concept of disaster resilience, which describes the ability of a system, community or society to resist, absorb, accommodate and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions (UNISDR 2009). However, resilience does not necessarily entail an ability to maintain or return to an exact pre-disaster state and a vital component of many resilient systems is their capacity to *adapt* to changing conditions. Mangrove forests, for example, migrate inland, if able, in response to sea level rise. As mentioned above, these diverse ecosystems have also proven able to mitigate the impacts of storm surges and tsunamis, enhancing the resilience of communities along tropical and subtropical shorelines (Huxham et al. 2010; McIvor et al. 2013; Jayasurya 2007).

Case study: Building coastal resilience – bamboo wave barriers in Thailand

"I find the sea level becoming higher and higher each year. Storms are more frequent and unpredictable. If the situation continues, we may have nowhere to live." — Kanit Sookdang

An innovative mangrove restoration project in southern Thailand has used ecological engineering to mitigate the impacts of coastal storms and erosion. Klong Prasong is a fishing village located on Klang Island in the Krabi river estuary along Thailand's Andaman sea coast. For many years, powerful waves, strong winds and rising sea levels threatened the village and its inhabitants, eroding the shoreline, damaging infrastructure and properties, and forcing villagers to relocate to higher land. Local fishermen report that waves have eroded the coastal area by more than 1 km and Kanit Sookdang, a 54-year-old villager from Klong Prasong, has been forced to move house five times in the past three decades due to coastal erosion (Sarnsamak 2014; BP 2014).

Representing socionatural disasters, the storms and coastal erosion experienced in Klong Prasong can be attributed to a complex interplay of natural and anthropogenic factors, including the monsoon climate, intensive shrimp cultivation and the effects of climate change. This multifaceted risk profile is further complicated by the increasing frequency and severity of coastal erosion and storm conditions over the past few years, an intensification which demonstrates the dynamic nature of disaster events over time and calls for a new approach to disaster management on Klang Island.

Observing the ineffectiveness of a concrete barrier wall constructed in 2003 – which, despite being raised in height, failed to protect communities and actually augmented sediment loss and the effects of coastal flooding – a community-initiated demonstration project under Raks Thai Foundation's "Building Coastal Resilience to Reduce Climate Change Impacts in Thailand and Indonesia (BCRCC)" initiative adopted a true EbA. It constructed a bamboo wave barrier in an attempt to address coastal erosion and facilitate the re-establishment of mangrove forests (Enright and Nakornchai 2014; Raks Thai 2014).

It is anticipated that the bamboo wall will reduce wave energy, mitigate erosion and foster the accumulation of sediment on its landward side in which mangroves can be planted. The structure – made from bamboo sourced locally in Krabi province – is expected to last approximately seven years, sufficient time to enable mangroves to form a natural bioshield. The dense network of trunks, branches and aerial roots of mangroves help shelter coastlines from strong winds and generate a high drag force, which attenuates waves and dissipates their energy across the intertidal zone (McIvor et al. 2012; Alongi 2008; Feagin et al. 2010; Giri et al. 2008). Mangroves have, in a number of instances, been observed to significantly reduce the impacts of storm events on coastal communities, reducing economic damages, mitigating biodiversity losses and saving lives (Das and Crépin 2013; Quartel et al. 2007; Kathiresan and Rajendran 2005; Badola and Hussain 2005).

While community members and visitors in Klong Prasong will be directly involved in the planting process – planting locally raised seedlings helps to build stewardship, awareness and support for the project – the bamboo barrier will also facilitate natural regeneration, trapping floating mangrove propagules to yield a forest with a high level of biodiversity. It is widely accepted that multispecies systems have greater ecological resilience than monospecific forest stands, and are thus more capable of mitigating natural disasters. Heterogeneous forests also provide a greater range of opportunities for livelihood diversification, demonstrating that ecological restoration, DRR and socioeconomic development are mutually reinforcing (MAP 2012; Jayakody et al. 2012; Vickers et al. 2012).

In addition to enhancing the resilience of coastal communities to disasters, mangrove forests generate other benefits by filtering water, absorbing CO_2 and providing a breeding habitat for aquatic animals (Enright and Kaewmahanin 2012; Sudtongkong and Webb 2008; Barraclough and Finger-Stich 1996). Accordingly, it is hoped that the re-establishment of mangrove forests along the coast of Klong Prasong will restore local biodiversity and ecosystem functioning for livelihood support, improved local food security and enhanced community health and well-being.

Although budget restrictions meant that only a single-layer bamboo barrier was constructed under the BCRCC project, the demonstration of this innovative approach to disaster management convinced the Krabi Provincial Administrative Office to build a more substantial, 500 m long double-layer bamboo barrier, supported with government investments of 1 750 000 Baht (US$ 55 000). This illustrates a new commitment by the government to ecosystem-based DRR approaches (Enright and Nakornchai 2014).

While it is too early to evaluate the long-term impacts of these bamboo wave barriers, a number of successes have already become apparent. Only eight months after the bamboo was first put in place – in June 2013 – assessments found that 15 cm of sediment had accumulated behind the structure, with a clearly visible difference in soil strata height between the seaward and landward sides. Planted *Avicennia marina* seedlings had a survival rate of 80–90%, compared with rates of just 10% when the same species was planted in front of the concrete wall. Significant increases have also been recorded in the biodiversity and population sizes of aquatic species, particularly molluscs: *Musculus senhousia, Donex scortum* and *Meretrix* sp. Local people can now expect to collect at least 3 kg of *Donex scortum* each during every collection session – a few hours during the low tide when the mudflats are exposed – which they had been unable to do in the recent past (Enright and Nakornchai 2014).

This innovative approach to disaster resilience has also had a positive impact on the mental health and well-being of community members in Klong Prasong. Village residents reported that they used to sleep uneasily with the sound of strong waves hitting the concrete wall and a constant fear that seawater would flood their homes. The construction of the bamboo barrier has increased their sense of security and allows them to sleep peacefully in the knowledge that they are better protected.

Sources: Enright and Nakornchai 2014; Raks Thai 2014

The above case study demonstrates best practice in the use of an EbA for the mitigation of disaster risk. The construction of bamboo barriers and concomitant regeneration of mangrove ecosystems off the coast of Klong Prasong has built the resilience of coastal communities, restored local biodiversity, and supported the revival of a number of livelihood opportunities for a more prosperous present and sustainable future.

Together, the case studies in this section demonstrate the ways in which well-managed ecosystems are able to prevent or mitigate the impacts of natural disasters, contributing to DRR by building resilience to diminish the effects of exposure, or fostering resistance to avert an event altogether. They also show that – through the rehabilitation and conservation of ecosystems and a concomitant enhancement of biodiversity – EbAs afford a range of environmental and socioeconomic benefits, which address multiple drivers of vulnerability, as well as improve the ability of communities to avoid, withstand and recover from the impacts of disaster (ProAct 2008). Finally, EbA measures have been seen to provide a dynamic, adaptable and innovative disaster management response, which is vital in a world of emerging and continually evolving disaster risks (van Slobbe et al. 2013).

3. Specific considerations for internally displaced persons and refugees[2]

Disaster events – whether driven by anthropogenic or natural factors, or a combination of both – are a major cause of population displacement, either within or across national borders. In 2011, some 14.9 million people became internally displaced due to natural disasters, the majority of them across Asia (UNHCR 2014). Current predictions regarding climate change as well as recurrent civil conflicts and cases of political unrest will likely lead to further displacements in the future, forcing people into marginal lands, and urban and peri-urban settlements.

This section describes the complexity of the relationship between displaced populations and biodiversity, which can be seen as simultaneously symbiotic and destructive. An exploration of the dependence of refugees and IDPs on ecosystem goods and services – during a crisis, in its immediate aftermath and during the longer-term post-disaster phase – is followed by an examination of the impacts that humanitarian operations can have in terms of the overexploitation and rapid degradation of natural resources, exposing an ironic situation in which those resources upon which communities may be most reliant are the ones being degraded or destroyed.

Although displaced populations are sometimes blamed for causing environmental degradation in the areas where they are forced to settle, it is extremely difficult to distinguish refugee/IDP impacts from other processes of ecosystem decline. As such, the contribution of these groups to biodiversity loss is sometimes overstated, while the important role they can play in ecosystem conservation and restoration can be understated or overlooked.

3.1 Refugees/IDPs rely on biodiversity/ecosystem goods and services

The survival and longer-term well-being of refugees and IDPs – in addition to host communities living within the vicinity of camps – is often dependent on particular natural resources, and the availability and accessibility of certain ecosystem goods and services. In the short term, these may provide *immediate* assistance for displaced populations at the onset of a crisis, during the event and in its direct aftermath. Supporting the realization of basic needs, for example, building materials for rudimentary shelters are typically sourced

[2] The 1951 Refugee Convention defines a **refugee** as someone who "owing to a well-founded fear of being persecuted for reasons of race, religion, nationality, membership of a particular social group or political opinion, is outside the country of his nationality" (UNHCR 2014). Notably, this definition excludes environmental drivers of population displacement and refugees may also be forced to migrate due to natural disasters although, in many cases, environmental disruptions result in internal migration rather than relocation to another country (Hyndman 2009). Unlike refugees, **internally displaced persons (IDPs)** have not crossed an international border and remain within their home countries, retaining the rights and protection afforded by citizenship under both human rights and international humanitarian law. The taxonomic distinction of these groups serves to mask a number of shared characteristics, as well as concealing considerable internal heterogeneity in terms of backgrounds and experiences. As such, the term "displaced populations" is used here to denote both refugees and IDPs (Oucho 2007).

from local forests, while wild foods and natural medicines may be collected for direct consumption or sale. This was observed in 1994, when intense ethnic fighting in Rwanda drove an estimated 600 000 refugees into an area surrounding Tanzania's Burigi National Park. In addition to the serious habitat destruction caused by widespread tree cutting, the high demand for food that accompanied the arrival of the refugees caused wildlife in the park to decline sharply. According to a report by TRAFFIC (Jambiya et al. 2007), large mammal populations declined by 60% between 1994 and 1997, at the peak of the refugee influx, and some wildlife populations were reduced to less than 10% of their former numbers. Buffalo (*Synceros caffer*) numbers fell from about 2670 to just 44, the roan antelope (*Hippotragus equinus*) and zebra (*Equus quagga*) populations declined from 466 to 15, and 6552 to 606, respectively, and the Lichtenstein's hartebeest (*Sigmoceros lichtensteinii*) vanished completely.

In the longer term, biodiversity can support a range of livelihood activities. Displaced populations have been known to *utilize* wild resources in opportunistic ways – for example, through charcoal making and the trading of bushmeat and firewood – demonstrating a more complex relationship than simple passive dependency. Such activities are often driven by numerous factors, including mounting population pressures, a lack of employment and income-generation opportunities, ineffective law enforcement, food insecurity and the inability of humanitarian assistance to accommodate dietary and culinary needs and customs (Jambiya et al. 2007). While resource-based livelihoods have helped displaced communities to enhance their resilience to disaster risks and eschew a dependence on external organizations, caution must be exercised as the extraction of certain natural resources can quickly wreak havoc on ecosystems if not appropriately managed and monitored, as the example from Burigi National Park above illustrates.

The collection and sale of firewood and production of charcoal are among the few options for income generation available to refugees and IDPs – who are typically denied the right to formal employment – and represent two of the most commonly adopted natural resource-based livelihood activities in camp settings. Unfortunately, these activities place considerable additional pressure on already stressed ecological systems and have led a number of host governments to adopt measures to reduce further environmental degradation, such as the implementation of encampment policies (e.g. Kenya and Tanzania) (UNHCR 2002; 2014b). In most instances, however, policies restricting the movement of displaced populations are poorly enforced and have failed to conserve natural resources. They have also encouraged the uptake of negative coping strategies (such as illicit resource gathering and sale of food rations), inhibited self-reliance and fostered dependency (Lyytinen 2009; Ahlsten et al. 2005).

More sustainable income-generating opportunities could incorporate environmental conservation and restoration, and several experiences have demonstrated the benefits of directly involving displaced populations in schemes to protect, enhance and sustainably utilize biodiversity and ecosystem goods and services in and around camp settings (Lyytinen 2009).

While it is clear that displaced populations draw upon a range of ecosystem goods and services to satisfy immediate survival needs and to support long-term health and well-being, self-reliance and livelihood security, these groups – as well as humanitarian efforts to assist them – typically present a dual threat to biodiversity and public health.

3.2 Humanitarian operations can pose dual threats to biodiversity and human well-being

Environmental degradation is inevitable in refugee/IDP situations. Displaced populations and associated humanitarian operations – which are in some instances poorly planned and coordinated – place considerable pressure on ecosystem goods and services. Deforestation for shelter construction and fuelwood, the extraction and pollution of groundwater and livestock grazing are among the most extensive ecological

Case study: Rwandan refugees in Gihembe National Park

In Rwanda's Gihembe camp, agricultural activities have fostered economic self-reliance for refugees who cultivate mushrooms to enrich their diets and generate income. With support from the American Refugee Committee (ARC), an association of 50 women living with HIV/AIDS has been established and supported to pursue commercial agriculture. The women have received extensive training on a range of topics – including association ethics, marketing, basic accountancy and business development – and encouraged to employ sustainable land management techniques for the conservation of ecological resources, minimizing soil and water erosion through terrace construction, trench digging and the planting of 780 agro-forestry trees (ARC 2014).

In seven months, 3700 kg of mushrooms have been harvested, with 3000 kg sold to camp residents, host community members and a local mushroom farm company (at around 1000 Rwandan francs [US$ 2] per kg) and the remaining 700 kg divided between the members of the association for domestic consumption (Gonzalez 2006).

In addition to providing nutritional benefits, this project has encouraged money management and a culture of saving has begun to develop among the women. The association account contains over 1.5 million Rwandan francs (US$ 2200), a third of which is shared as profit among members and stored in fixed deposit accounts to accrue interest (ARC 2014). This resource-based income-generating project has also contributed to fighting the stigma surrounding HIV in the camp. Refugees and members of the host community who purchase the mushrooms have been made aware that those living with this disease are still able to work productively and contribute to life in Gihembe, reducing prejudice and enhancing the quality of life for all those with HIV (ARC 2014).

The agricultural activities in Gihembe refugee camp demonstrate that well-managed ecosystems are capable of providing a direct source of livelihoods for displaced populations. With active participation and capacity building, the refugees were able to help themselves, utilizing locally available natural resources to rebuild and improve their lives in a dignified and sustainable manner (UNHCR 2014).

threats engendered by the sudden arrival of large numbers of people. This results in the loss of indigenous plant and animal species and a substantial decline in biodiversity (Oucho 2007). With time, ecosystem degradation may spread beyond the immediate confines of a camp, where other disaster response activities might be under way. In north-east Kenya's Dadaab refugee camp, for example, the deforestation radius around the camp increased from 5–10 km to 70 km between 1990 and 2010 (Gitau 2011).

Any additional stress to existing environmental degradation will not only have significant implications for displaced populations (whose livelihoods and well-being are likely to depend to some degree on the goods and services provided by local ecosystems), but will also impact members of host communities.[3] The establishment of a refugee/IDP camp and the subsequent influx of thousands of people (potentially from different ethnic and cultural backgrounds) change the environment of host communities in both positive and negative ways. In most cases, initial kindness gives way to hostility as biodiversity is diminished and resource scarcities arise, inciting tension between the newcomers and host community members, which can result in conflict

[3] Host communities comprise the local, regional and national political and socioeconomic structures within which refugees live (UNHCR 2014).

Case study: Pressure on water resources: Syrian refugees in Jordan

Jordan is one of the world's most arid countries but, since 2011, potential threats to water and food security have been exacerbated by the arrival of over 600 000 Syrian refugees. This population influx has accelerated groundwater depletion and caused water tables to drop precipitously, increasing salinization and rendering what little water remains less safe for human consumption.

Jordanian households use an estimated 80 L of water per day on average, but communities in which refugee camps have been established have seen the average supply drop below 30 L per day, with accompanying declines in sanitation and a rise in disease incidence. As the quality and quantity of limited water reserves continues to deteriorate, attention has turned towards demand and the poor water conservation habits of Syrians, who are unaccustomed to living in a water-scarce environment and are thus prone to wasting water.

Future efforts at water management must be implemented with long-term sustainability in mind in order to preserve natural resources, support their restoration and maximize public health benefits. A holistic approach incorporating water demand management could also include the promotion of simple and culturally appropriate conservation practices at the household level in order to reduce water consumption and facilitate the possibility of groundwater replenishment.

Source: Mercy Corps 2014

(UfS 2013). The case studies below illustrate the myriad impacts displaced populations can have on biodiversity in their hosting areas.

While the examples given above illustrate the detrimental effects that humanitarian operations can have on biodiversity, ecosystem functioning and sustainability, this need not always be the case. It must be recognized that the environments which displaced populations enter are not necessarily pristine, but are usually already undergoing various processes of degradation and decline. It is not uncommon, though, for these groups to be blamed for declining conditions that predate their arrival, particularly where environmental baseline data and monitoring are unavailable (Oucho 2007).

The presence of Mozambican refugees in Malawi's Dedza and Ntcheu districts, for example, had little discernable impact on soil fertility or the depletion of many other natural resources (Barnett 2003). Although most Mozambicans made use of tree products – notably for fuelwood and construction poles – little overall difference was noted in the rates of forest coverage between refugee and non-refugee affected areas. Refugees rarely felled trees for fuelwood alone – collecting most of it from the ground or as a byproduct of trees felled for other purposes. The main environmental change caused by refugees has been a decline in woody biomass.

Localized instances of deforestation and considerable variation in the extent of woody biomass depletion throughout Dedza and Ntcheu districts – even in areas subjected to similar human pressures – demonstrate that the simple presence of refugee communities does not necessarily lead to biodiversity loss. This heterogeneity is an outcome of interactions between various local environmental and sociocultural factors, such as the presence and enforcement of informal regulations and established norms of resource access (Barnett 2003). The ways in which refugee livelihoods interact with the environment are complex and diverse, with substantial differences often discernable between, and within, specific locations.

Refugees and IDPs can make a significant contribution to conservation and rehabilitation efforts. In a number of West African countries, for example, the presence of displaced populations led to the transfer of skills for sustainable cultivation, plant management and resource-based entrepreneurship between these groups and host communities, as well as fostering improved environmental consciousness and awareness of conservation issues (Oucho 2007).

As mentioned above, strategies to reduce environmental degradation and restore ecosystems offer the potential to provide much-needed income-generating opportunities in refugee and IDP situations as well as enhance biodiversity. A number of successful projects demonstrate the benefits of collaborating with displaced populations as well as host communities for effective and contextually appropriate disaster responses, which reduce the risks associated with further resource overexploitation and provide livelihood support for impacted groups.

In Dzaleka refugee camp in Malawi, refugees have established the "Education and Plantation Strategies Association" (EPSA), which aims to boost local incomes through the planting of 6000 fruit trees both within and beyond the camp's limits. EPSA members grow seedlings from the fruit they eat and have started a small nursery near the camp, while the running of a sustainable agriculture and gardening course has seen the creation of a community garden and the introduction of a permaculture project for additional livelihood opportunities (Stapleton 2014).

This section has illustrated the complex nature of the relationship between displaced populations, biodiversity, human security and well-being. While refugees and IDPs often rely directly on local ecosystem goods and services to meet a range of short- and long-term needs essential to their well-being, the ongoing degradation and overexploitation of natural resources in and around settlements threaten their ability to fulfil basic daily requirements, partake in sustainable livelihood activities and achieve autonomy. There is therefore an urgent need for context-specific and participatory interventions to reduce the demands placed upon local ecosystem goods and services by displaced populations, and to foster the more sustainable extraction and utilization of natural resources. As this chapter has demonstrated, integrative, cross-sectoral approaches, such as the ecosystem approach, are required and may hold the key to meeting these challenges.

UNDP BANGLADESH / FLICKR

STEPHAN BACHENHEIMER

15. Population, consumption and the demand for resources; pathways to sustainability

1. Introduction

The large-scale transformations of ecosystems to meet the needs of growing human populations have greatly accelerated over the past century, transforming up to three quarters of the Earth's biosphere, and diverting much of its biological productivity for human use (Brown 2004; MEA 2005; Ellis & Rammankutty 2008; Steffen et al 2015). The growing conversion of land for agriculture, pasture, energy and commercial development has grown steadily alongside the extraction of natural resources, the erosion of landscapes and the unabated loss of the Earth's genetic and species diversity.

While many of these developments have benefitted the lives of millions of people, improving their access to food, shelter, energy, water and other resources, they have often come at the expense of human health and the ecosystems upon which we all rely for our survival (MEA 2005). They have also inevitably altered the nature and functions of many of our ecosystems, in turn shaping the burdens of disease and inequity, across geopolitical boundaries, from local to global scales (Robbins 2011).

The previous chapters describe the multitude of linkages between biodiversity and human health. They also note that there are common drivers of change to biodiversity and human health (see chapter 2, in particular). The linkages and the origins and impacts of the drivers occur at various spatial scales and have a wide range of implications for human well-being.

This chapter looks at the underlying drivers of change and their current trends. It examines possible future scenarios of change and their implications for biodiversity, human health, and the interactions between them. Looking at future scenarios can be useful in elucidating potential synergies and tradeoffs in policies for health and biodiversity conservation as well as in examining the feasibility of meeting health and biodiversity objectives in the context of broader goals such as the emerging sustainable development goals.

In recent decades, there has been an increased interest in the implications of environmental change for human health (WHO 2005), often with a particular focus on the impacts of climate change (See Chapter 13). More recently still, the importance of biodiversity and its decline for human well-being has been also highlighted (Cardinale et al 2012). In fact, threats to human health from climate change and biodiversity change need to be addressed together, in a coherent framework. This is necessary not only because of the interactions between the impacts on human health due to climate change and those due to biodiversity change (see Chapter 13), but also because consideration needs to be given to the potential tradeoffs and synergies in addressing these challenges.

Addressing the direct and underlying drivers of biodiversity loss, poverty and ill health, under present and future challenges also ultimately requires behavioural change by individuals, communities, organizations, industries, businesses and governments. Understanding, awareness and appreciation of the diverse values of biodiversity, ecosystems and the services they deliver underpin the combined willingness of millions of individuals to undertake purposeful actions to address these drivers of change (see Chapter 16). Greater awareness of the values of biodiversity and ecosystem services also allows individuals and governments to assess more accurately the trade-offs of their policies and decisions (CBD, 2013).

2. Current Trends and Alternatives

1.1 Population pressures

The increase in the exploitation of natural resources since the 20th century is in part attributable to a rapid and sustained increase in the global population.. The world population, now 7.2 billion people, will likely increase to between 9.2 billion and 9.9 billion in 2050 and between 9.6 billion and 12.3 billion in 2100 (80% probability levels). Much of the increase is expected to happen in Africa, in part due to higher fertility rates and a recent slowdown in the pace of fertility decline (Gerland et al. 2014). While population is expected to decline in some regions, notably in Europe, the overall global population is expected to increase, on average, by over 10% through to 2030, with the largest population growth occurring in low and low-to-middle income countries (UN-DESA 2015). The greatest population density has also been projected to occur across areas that are already densely populated, including coastal regions in which communities are facing sea level rise and other threats posed by climate change (The Earth Institute, 2006). The highest birth rates and largest increase in number of women of reproductive age are expected in Africa, where the highest rates of maternal and child mortality persist, and access to family planning is lowest (UN DESA, 2015).

Population growth may have some positive consequences. For example, some economists have argued that population growth induces technological innovation, and provides development benefits including agricultural innovation and intensification (e.g. Boserup 1965; Das Gupta 2011). However, population expansion also places increased demand on healthcare systems and can greatly extenuate pressures on natural resources. In particular, rapid population growth in high fertility countries can create a range of economic, social, health and environmental challenges as well as for governance (lagging investments in health, education, and infrastructure). (Brown 20014; Bongaarts 2013; Gerland et al 2015)

Among the most robust empirical findings in the literature on fertility transitions are that higher rates of contraceptive use and female education are associated with faster fertility decline (Hirschman 1994; Sen 1999). These suggest that the projected rapid population growth could be moderated by greater investments in family planning programs to satisfy the unmet need for contraception (Petersen et al 2013), as well as investments in girls' education.

Greater investment in the education of girls and women, improved access to and awareness of birth control and family planning would not only improve human health and well-being directly, it would also help slow and reverse trends among countries with the highest projected growth rates and concomitant pressures on ecosystems (Speidel et al. 2007; Sachs 2008; Population and Environment 2007). However, in many cases, economic development and healthcare systems have not kept apace with the growing needs of the fastest-growing populations, particularly in low-income countries already struggling to expand healthcare services to women and girls (The Lancet 2012). In regions with the highest projected population growth rates, notably Sub-Saharan Africa, there remains a largely unmet need for access to contraception, a reduction of unwanted pregnancies, and the implementation of family planning policies (Ezeh et al. 2012).

3. Consumption – the demand for food and energy

Global demand for food, energy, water, shelter and healthcare has risen dramatically over the past 100 years, and this trend is likely to continue, leading to a new set of interrelated conservation, public health and development challenges (Eg.: Tillman and Clark 2014; Neff et al. 2011; Costello et al. 2009). The resulting pressures on natural ecosystems, including biodiversity loss, may not only lead to increased competition for food, water, energy and land, affect economies, and bring us closer to "tipping points" (Leadley et al 2010, 2014; See also Chapter 2); they will also have major implications for global public health, with disproportionate impacts on the poor and vulnerable.

While population growth contributes to this increased demand, its impact is dwarfed by the effects of rising consumption by more prosperous members of the global community. The "ecological footprint" provides an estimate of the per capita impact of consumption on biodiversity and ecological systems. It is measured in "global hectares", with the earth able to support the current population with just under two global hectares per person. Most countries in Africa have per capita footprints well within this value, while the per capita footprint in Western Europe is about and in North America about (Wackernagel, 1994; Global Footprint Network, 2015).

With respect to greenhouse gas emissions, Satterthwaite (2009) notes that significant proportion of the world's urban (and rural) populations have consumption levels that are so low that they contribute little or nothing to such emissions. He concludes: "if the lifetime contribution to GHG emissions of a person added to the world's population varies by a factor of more than 1,000 depending on the circumstances into which they are born and their life choices, it is misleading to see population growth as the driver of climate change".

According to a recent study 1.3 billion people worldwide do not have access to an electric grid (IEA 2013), including over three quarters of the population (or 600 million people) in Africa alone (IEA 2011). This leads to an estimated 600 000 preventable yearly deaths from indoor fumes (UNEP 2015a). According to recent UN estimates, the burning of fossil fuels for lighting accounts for 90 million tonnes of CO_2 annually (UNEP 2015b), and an additional 270,000 tons of black carbon emitted as a result of kerosene lamps for lighting (UNEP 2015a). Without adequate measures, the number of people without access to an electric grid in Africa is projected to increase to 700 000 by 2030, further extenuating pressures of climate change on ecosystems and public health (UNEP 2015a). Thus efforts to reduce the use of emissions from fossil fuels must be accompanied with efforts to provide modern energy for all.

A well-nourished global population expected to exceed 9 billion by 2050 would require an estimated increase in food production ranging between 70% and 100%, with a corresponding rise in demand for processed foods, meat, dairy and fish as populations become more urbanized (Godfray et al. 2010; Royal Society of London 2009). Tilman and Clark (2014) note that dietary trends towards diets higher in refined sugars, refined fats, oils and meats, could lead to land clearing for agriculture and an 80% increase in associated greenhouse gas emissions. Such dietary trends would also increase the burden of disease from type II diabetes, coronary heart diseases and other chronic non-communicable diseases. However, as noted in Chapter 6, alternative diets (such as the Mediterranean diet), if widely adopted, would greatly reduce impacts on biodiversity and climate change and also improve health outcomes.

Water resources are projected to come under increased pressure, both as a result of increased pollution and demand. In developed and developing countries alike, water stress hinders economic growth and threatens food production systems and food security (Bogardi et al. 2012; Viala 2008; Brown 2004). As the chapter on freshwater indicates, this resource is consumptively used for agriculture, as well as domestic use, and, increasingly, by the industrial sector (Schwarzenbach et al. 2006), often to the detriment of the most vulnerable populations who have least access to health care, energy supplies and other essential services. The freshwater crisis mirrors those related to other ecosystem services, including the impact of sustained air pollution, and the decline of 'soil based' ecosystem services which affect crop yields and land productivity (see e.g. Barrios 2007).

Addressing increased pressures on natural resources, while also ensuring that the basic needs of all for food and modern energy are met, will necessarily need to greater emphasis on equality of access to and use of these natural resources. In fact, empirical research shows that more equal societies are also associated with better health outcomes, among other factors of human well-being (Wilkinson and Pickett 2009).

4. Global trends to 2050 and pathways to sustainability

Increasingly, scenarios of biodiversity change are being used to explore (Pereira et al. 2010). Most scenarios indicate that biodiversity will continue to decline over the 21st century. However, the range of projected changes is much broader than most studies suggest, partly because there are major opportunities to intervene through better policies (Pereira et al. 2010).

Recently, scenarios are also being used to explore alternative pathways for achieving globally agreed goals. For example PBL-the Netherlands Assessment Agency has developed scenarios to elucidate pathways to achieve the 2050 Vision of the Strategic Plan for Biodiversity 2011–2020, while also meeting other globally agreed goals (PBL 2012). These scenarios have been updated and extended for GBO-4 (see box) (CBD 2014; Kok, Alkemade et al (2014)).

Box 1: Global Biodiversity Outlook-4: A mid term assessment of progress towards the Aichi Biodiversity Targets

In 2014, the Conference of the Parties to the Convention on Biological Diversity assessed progress in the implementation of the Strategic Plan for Biodiversity 2011–2020 and its Aichi Biodiversity Targets. (See Chapter I, box 1, on the basis of an evaluation contained in the fourth edition of the Global Biodiversity Outlook (GBO-4; see also Tittensor et al 2014). The assessment shows that significant progress towards meeting the components of the majority of the Aichi targets. However, in most cases, this progress will not be sufficient to achieve the targets set for 2020 and additional action is required. The evaluation was based on multiple lines of evidence including global assessments extrapolated trends in 55 indicators to 2020 and 2050, including response indicators and indicators based on projections on the state of biodiversity. The conclusions are that while responses to biodiversity loss are increasing (i.e countries are taking action), the large majority of projections of the state of biodiversity to 2020 and 2050 show a significant deterioration and pressures on biodiversity continue to increase.

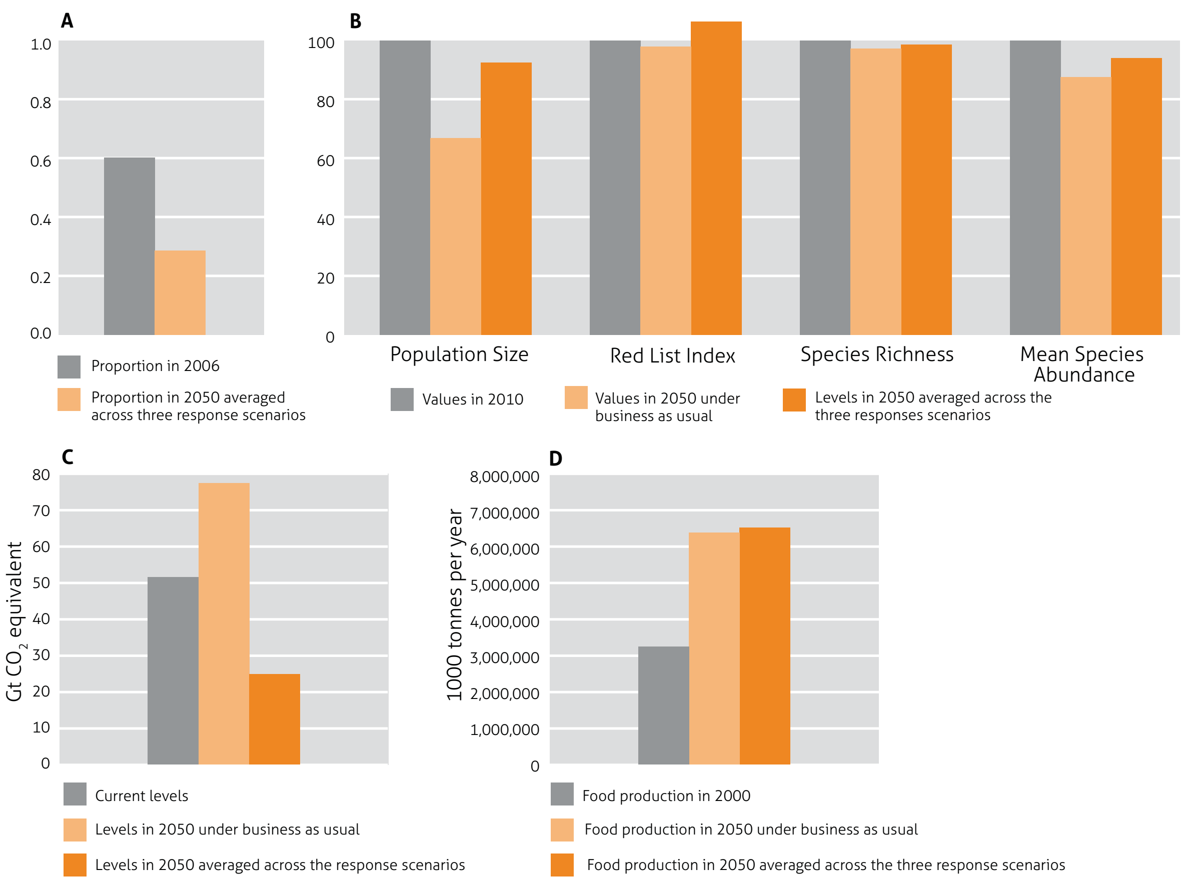
The Outlook also identifies actions that would help to accelerate progress and concludes that attaining most of the Aichi Biodiversity Targets will require implementation of a package of actions typically including: legal and policy frameworks; socioeconomic incentives aligned to such frameworks; public and stakeholder engagement; monitoring and enforcement. Coherence of policies across sectors and the corresponding government ministries is necessary to deliver an effective package of actions.

Business-as-usual scenarios were contrasted against plausible alternative scenarios to 2050 that would simultaneously curb biodiversity loss, mitigate climate change, alleviate poverty and, in so doing, contribute to maintaining essential ecosystem services that sustain human health (see Figure 1).

Drawing on the findings of the Global Biodiversity Outlook report described in the preceding section, the scenarios in Figure 1 suggest that there are multiple plausible pathways to simultaneously achieve the intersecting goals of maximizing biodiversity, human health, and development outcomes. Under these alternative scenarios, several biodiversity indicators reflecting the health of our ecosystems and the life-supporting services that they deliver would also be improved. (see Figure 2).

Under 'business as usual' scenarios, pressures of increased per-capita consumption and population growth, energy-intensive agricultural production that is both water and fossil fuel-intensive, unsustainable harvest, overconsumption, indiscriminate and unregulated large-scale exploitation of terrestrial and marine resources, the erosion of genetic diversity; pervasive use of pesticides, nitrogen fertilizers in food production systems and antibiotics, deforestation, illegal trade, perverse economic incentives, marginalization and alienation of poor and vulnerable populations, and lack of awareness and education on the values of biodiversity and ecosystem services, will all combine to exert untenable pressures on the biosphere and human populations alike. These pressures have been abundantly demonstrated throughout this volume. Fortunately, sustainable alternatives have also been proposed and evaluated.

FIGURE 1



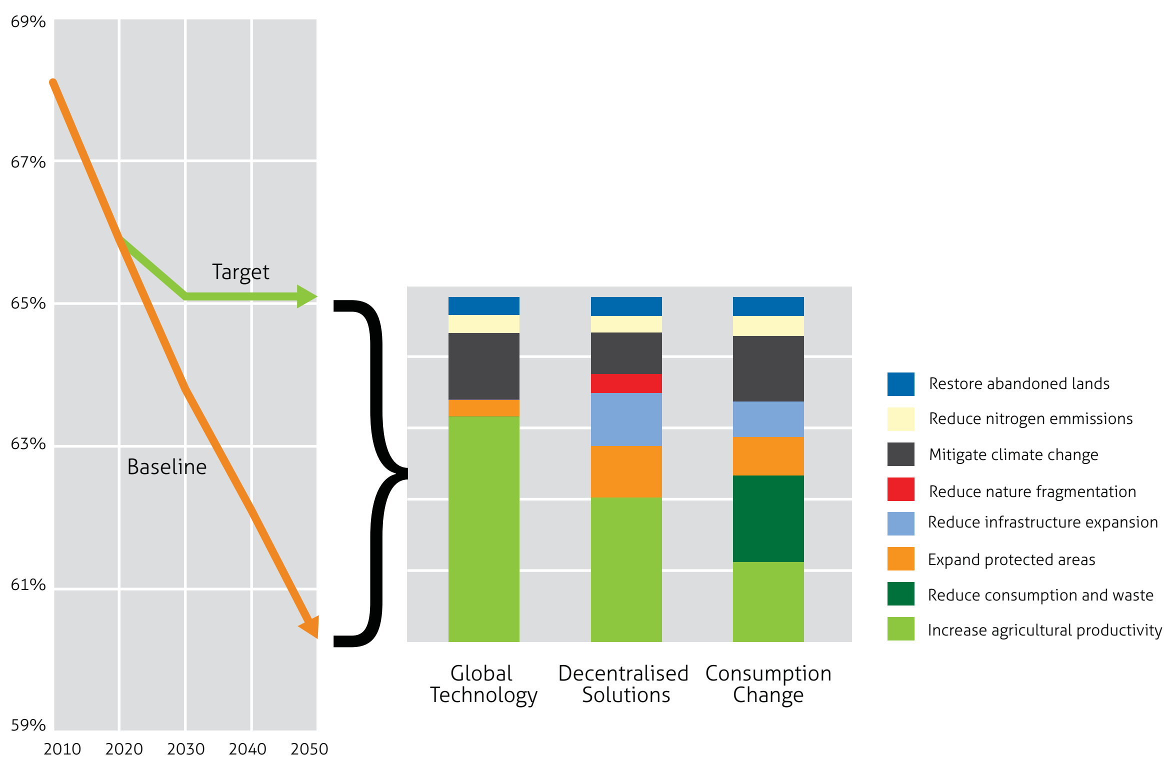
Common elements of the pathways identified in the preceding section include:

- Reducing greenhouse gas emissions from energy and industry (see also chapter on climate change);
- Increasing agricultural productivity and containing agricultural expansion to prevent further biodiversity loss and to avoid excessive greenhouse gas emissions from conversion of natural habitats (see also chapter on agricultural biodiversity);
- Restoring degraded land, protecting critical habitats and resources (see also chapter on freshwater);
- Managing biodiversity in agricultural landscapes
- Reducing post harvest losses in agriculture and food waste by retailers and consumers as well as moderating the increase in meat consumption (see also chapters on agricultural biodiversity and nutrition);
- Reducing nutrient and pesticide pollution and water use (see also chapters on freshwater and air quality and impacts of pharmaceuticals on the environment);
- Promoting sustainable harvest, use and trade of resources used for medicines (see also chapter on traditional medicine).

As the scenarios in Figure 2 and practical experience demonstrate, it is possible to achieve these goals while achieving food security, protecting biodiversity, curtailing climate change and attaining other goals for human development.

Improvements in energy production, transmission, end-use and resource use efficiency, are needed, along with a transition toward the decarbonization of energy supplies (Neff et al. 2011; Peñuelas 2010; Horton 2007). As noted above, this must be accompanied by improved access to modern energy for all. Trends associated with globalized

FIGURE 2



industrial food production systems that are highly reliant on petroleum for the development of pesticides, industrial agriculture, and the transportation of food, can only be reversed through the development of a robust package of economic measures and policies which includes taxes on carbon and economic policies that mitigate the perverse impacts of energy policies (Horton 2007; Flora 2010). Pollan (2008) argues that reform of agricultural systems is needed to meet health, food safety and energy challenges.

The important role of public health in enabling a smooth transition toward more proactive, sustainable and equitable social and policy transitions toward less fossil-fuel dependent and resilient food production systems also cannot be overstated (Neff et al. 2011). At the national level, these changes will need to be complemented by increased equality in access to and use of energy and other natural resources and in access to healthcare and the provision of related infrastructural innovation. For example, using indoor wood-burning stoves to increase food security (or for heating) is counterproductive as exposure to indoor air pollution is responsible for a staggering number of preventable deaths[1] and illnesses each year.

Many of the routine human behaviours that together define the functioning of the global economy will need to be altered if these goals are to be realized, requiring transformational change at the at the global, national and personal levels (Horton, 2007; Schwartz 2011). Managing, and benefiting from, the interlinkages between biodiversity, ecosystems services and human health increasingly demands broad-scale interventions that effectively and sustainably influence human behaviour (Freya et al. 2010; Fulton et al. 2011; The Lancet 2015; see also Chapter 16).

5. Conclusion

As we embark toward a new sustainable development agenda in 2015, the identification and prioritization of strategies that jointly deliver environmental (including biodiversity) and socio-economic (including health and development) co-benefits will be both a key challenge and opportunity. Interlinked efforts to reduce the ecological footprint of development, including stressors on biodiversity, energy demand, and health services provision, will be strategic priorities.

Population growth, and prevailing consumption and production patterns are but part of these challenges, however: population movement, for example, also causes environmental stress. Conflict prevention can help reduce the environmental impact of large congregations of displaced persons in refugee camps (Burkle 2010; see also chapter 14 in this volume). Similarly careful environmental impact assessment can mitigate the effect of communities displaced by large-scale development projects. The ecological footprint of city growth and urban pollution, and associated health impacts described in previous chapters can be limited by long-term urban planning. In all these cases a mixture of conservation, public health and social sciences, demography, and policy planning is needed to avoid the worst-case scenarios wherein resource scarcity, ecosystem degradation, biodiversity loss, human conflict, and climate change combine to present the perfect storm of multiple, simultaneous, ongoing humanitarian crises. As further described in the following chapter, the architects of coherent strategic policies integrating the biodiversity and health nexus must harness these opportunities and reflect these imperatives for the health and well-being of present and future generations.

[1] Based on World Health Organization estimates, in 2012, approximately 4.3 million premature deaths were attributable to household air pollution.

16. Integrating health and biodiversity: strategies, tools and further research

1. Introduction

The various interlinkages between biodiversity and human health have been surveyed in the preceding chapters of this volume. Table 1 provides a summary of the some of these interlinkages and how the health sector might respond. As has been demonstrated throughout this volume, biodiversity and ecosystems should be viewed as part of the overall public health management landscape, and a vital resource for promoting public health and healthy lifestyles, in the prevention of disease – both communicable and noncommunicable. (chapters 5, 6, 7, 8, 12). A careful identification and assessment of common drivers (chapter 2) includes land use change (chapters 5, 7, 15), invasive species (chapters 3, 7), over-exploitation of resources (chapters 9, 11, 15), habitat loss (chapter 7), climate change (chapter 13), and the unintended consequences of human activity (chapters 4, 5, 6, 7, 8, 9, 10), which can range from antibiotic resistance (chapter 5, 8, 9, 10), to endocrine disruption (chapter 3) to air pollution (4) and climate change; each of them further compounded by urbanizing and population pressures (chapters 5, 6, 15)

This final chapter considers some possible strategies and tools for promoting the integration of biodiversity and health objectives, especially in policies, programmes and practices at national level. Building upon consultations among countries organized by the CBD Secretariat and the World Health Organization through an ongoing series of workshops (Romanelli et al, 2014b; Box 1), the chapter outlines some objectives for such strategies and provides a list of preliminary list of priority interventions at country level. The chapter then considers a number of tools and approaches that could support such strategies, including common metrics and approaches, methods and indicators for monitoring progress, and tools and approaches for economic valuation. Building on the analysis in Chapter 15, the chapter also considers approaches for promoting behavioural change.

A discussion of needs for further research on the interlinkages between health and biodiversity is also provided.

Finally, the chapter discusses the integration of biodiversity-health linkages in the post-2015 sustainable development agenda.

2. Strategic objectives for the integration of biodiversity and human health

The linkages between biodiversity and human health presents a broad range of opportunities for jointly protecting health and biodiversity, and for advancing human well-being. More specifically, health and biodiversity strategies

Table 1 : Some key biodiversity-health linkages

Biodiversity and Health Topic	Health Sector Opportunity
Water • Water quantity • Water quality • Water supply	Direct responsibility: • Integrate ecosystem management considerations into health policy *Indirect responsibility:* • Promote protection of ecosystems that supply water and promote sustainable water use
Food and nutrition • Species, varieties and breeds including domesticated and wild components • Diversity of diet • Ecology of production systems • Total demand on resources • Sustainability of offtake, harvesting and trade of species used for food • Changing status of species used for food	Direct responsibility: • Recognize and promote dietary diversity, food cultures and their contribution to good nutrition • Recognize synergies between human health and sustainable use of biodiversity (e.g. moderate consumption of meat) *Indirect responsibility:* • Promote sustainable production harvesting and conservation of agrobiodiversity
Diseases • Disease source and regulation services • Ecosystem integrity and diversity	Direct responsibility: • Integrate ecosystem management considerations into health policy *Indirect responsibility:* • Promote ecosystem integrity
Medicine • Traditional medicines • Drug development (genetic resources and traditional knowledge) • Chemical/ pharmaceutical accumulation in ecosystems • Sustainability of offtake/harvesting and trade of medicinal species • Changing status of species used for medicine	Direct responsibility: • Recognize contribution of genetic resources and traditional knowledge to medicine *Indirect responsibility:* • Protect genetic resources and traditional knowledge • Ensure benefit sharing
Physical, mental and cultural dimensions of health • Physical and mental health • Cultural/spiritual enrichment	Direct responsibility: • Integrate 'value of nature' into health policy *Indirect responsibility:* • Promote protection of values, species and ecosystems
Adaptation to climate change • Ecosystem resilience • Genetic resources ('options' for adaptation) • Shifting reliance to biodiversity with climate change 'shocks'	*Indirect responsibility:* • Promote ecosystem resilience and conservation of genetic resources • Decrease vulnerability of people reliant on important food and medicinal species which are likely to be impacted by climate change

could be developed with the aim of ensuring that the biodiversity and health linkages are widely recognized, valued, and reflected in national public health and biodiversity strategies, and in the programs, plans, and strategies of other relevant sectors, with the involvement of local communities. The implementation of such strategies could be a joint responsibility of ministries of health, environment, and other relevant ministries responsible for the implementation of environmental health programs and national biodiversity strategies and action plans. Such strategies would need to be tailored to the needs and priorities of particular countries.

Such strategies might include the following objectives (this volume; Romanelli et al. 2014b):

(b) Promoting the health benefits provided by biodiversity for food security and nutrition, water supply, and other ecosystem services, pharmaceuticals and traditional medicines, mental health and physical and cultural well-being. In turn, this provides a rationale for the conservation and sustainable use of biodiversity as well as the fair and equitable sharing of benefits;

(c) Managing ecosystems to reduce the risks of infectious diseases, including zoonotic and vector-borne diseases, for example by avoiding ecosystem degradation, preventing invasive alien species, and limiting or controlling human-wildlife contact;

(d) Addressing drivers of environmental change (deforestation and other ecosystem loss and degradation and chemical pollution) that harm both biodiversity and human health, including direct health impacts and those mediated by biodiversity loss;

(e) Promoting lifestyles that might contribute jointly to positive health and biodiversity outcomes (e.g.: protecting traditional foods and food cultures, promoting dietary diversity, etc.)

Box 1: Workshops on the interlinkages between biodiversity and human health

In 2012, the WHO and the CBD embarked on an unprecedented joint collaborative endeavour aimed at engaging the health and biodiversity sectors worldwide, with a particular focus on developing countries, where concerted action is most urgently needed, in order to build capacity, and promote action to jointly protect biodiversity and promote human health in the context of sustainable development. The initial series of regional capacity-building workshops jointly convened by these organizations, in collaboration with national and regional country partners, were held for the Americas in Manaus, Brazil in September 2012 and for Africa in Maputo, Mozambique in April 2013. Country representatives from the biodiversity and health sectors from a combined total of some 50 countries, and a number of relevant organizations, regional experts and representatives of indigenous and local communities, gathered to survey some of the critical linkages at the biodiversity-health nexus and their relevance to the Strategic Plan and its Aichi Biodiversity Targets and to discuss the need to further mainstream biodiversity in public health strategies and to incorporate public health considerations in biodiversity strategies. Participants agreed upon an initial broad set of conclusions which have been further revised and adapted in light of the issues identified throughout various chapters of this state of knowledge review, in the broader context of the implementation of the Strategic Plan for Biodiversity 2011–2020 and the Post-2015 development agenda. These conclusions are reflected in sections 2 and 3 of this chapter as a broad framework for the integration of the biodiversity-health considerations in local, national and regional strategies (see also Romanelli et al. 2014b) .

(f) Addressing the unintended negative impacts of health interventions on biodiversity (e.g.: antibiotic resistance, contamination from pharmaceuticals), incorporating ecosystem concerns into public health policies, and

(g) Addressing the unintended negative impacts of biodiversity interventions on health (e.g.: effect of protected areas or hunting bans on access to food, medicinal plants, etc.).

Promoting and maximizing the health benefits provided by biodiversity for food security and nutrition, water supply, and other ecosystem services, pharmaceuticals and traditional medicines, mental health and physical and cultural well-being provide a strong rationale for the conservation and sustainable use of biodiversity and the fair and equitable sharing of benefits. Lifestyles (such as diets based on low-fat, diverse and nutritious foods), practices and actions (such as integrated land-use planning to maximize health benefits) will require educating, engaging and mobilizing the public and the health sector alike, including professional health associations as potential, powerful advocates for the sustainable management of ecosystems. It will also require mobilizing organizations and individuals who can articulate the linkage and the enormous value proposition investments in sustainable ecosystem management provide to the social and economic health of communities.

In the sections that follow, some tools to achieve these outcomes and additional areas for further research are identified. These are not intended to be comprehensive, but rather illustrative of the need to further strengthen interdisciplinary knowledge at the intersection of biodiversity and health.

A key element is adopting integrative approaches such as the "One Health" approach or other approaches that consider connections between human, animal, and plant diseases and promotes cross-disciplinary synergies for health and biodiversity (see section 4 of this chapter). In this context, the importance of preventive and precautionary strategies for the management of sustainable ecosystems to optimize health outcomes cannot be overstated (PEDRR 2013). For example, the chapters on disaster risk reduction and climate change demonstrate the need for a *proactive* approach to risk management by outlining examples from a growing portfolio of ecosystem-based adaptation and mitigation measures. "Enhancing disaster preparedness for effective response" comprises the fourth priority under the newly concluded Sendai Framework for Disaster Risk Reduction (2015–2030); well-managed ecosystems and the myriad of services they can provide will undoubtedly play an important role in achieving this target and removing, or at least reducing, the effects of natural disaster events on human life. The health status of populations exposed to extreme events is equally central to the overall success of the Sendai Framework, placing the health sector at the centre of prevention and mitigation strategies. The call for additional public and private investment alone, which is the third priority of the Sendai Framework, while essential, will not be sufficient to strengthen health systems or improve health outcomes.

Monitoring, evaluating and forecasting progress toward the achievement of national, regional and global targets at regular intervals against evidence-based indicators, including threshold values for critical ecosystem services, such as the availability and access to food, water and medicines is critical as further discussed section 5 of this chapter.

3. Priority interventions for the integration of biodiversity and human health

Romanelli and others (2014b) identified as of priority interventions to facilitate the integration of biodiversity-health linkages in relevant polices, programmes and practices at the national level. As they noted, the implementation of these interventions will be largely influenced by individual country institutional and financial capacities, and shaped by competing demands faced by health and environment agencies, with often limited resources. In that light, they suggest that a pragmatic approach is needed, focusing first on those activities which require little initial investment and which will gradually develop partnerships and capacities to deliver more efficiently on the shared agendas of health and conservation actors. These would likely include improved cross-sectoral collaboration mechanisms, the sharing of existing data and information, and the pooling of resources, where feasible. This would help to move beyond the confines of habitual institutional silos in which health and environmental policies are often developed, so interventions are no longer viewed as added burdens imposed by one sector on the other, but rather as important opportunities for collaboration toward improved health and conservation outcomes.

The priority interventions identified include.

(a) Encourage the development of new and existing tools such as environmental impact assessments, strategic environmental assessments, risk assessments, and health impact assessments that consider health-biodiversity linkages to manage future risks and safeguard ecosystem functioning while ensuring that social costs, including health impacts, associated with new measures and strategies do not outweigh potential benefits

(b) Strengthen core national capacities that enable health systems to prepare for and effectively respond to public health threats resulting from ecosystem degradation and undertake cooperative actions toward capacity-building that promote the training of professionals in the health and biodiversity sectors, as well as indigenous and local communities

(c) Promote research, development, and cooperation in traditional medicine in compliance with national priorities and international legal instruments, including those concerning traditional knowledge and the rights of indigenous peoples, as appropriate

(d) Promote the exchange of information, experiences, and best practices to support the development of national and regional biodiversity and health strategies, and integrated tools of territorial planning

(e) Disseminate and share lessons learned, knowledge, and national experiences related to biodiversity–health linkages among countries and with international, national, and local partners to facilitate the development of tools aimed at integrating biodiversity in health strategies and reflecting public health considerations in biodiversity strategies

(f) Carry out awareness raising activities and develop education programs on the importance of health–biodiversity linkages at various levels, so as to enhance support for policies and their implementation

(g) Promote further applied research on biodiversity–health linkages to identify country-specific health risks, notably through disease organisms or ill-health triggers that result from ecosystem degradation and address local health adaptation needs and solutions. Research should also contribute to strengthening inter-country and regional research collaboration to address knowledge gaps and to incorporate social and cultural perspectives as well as traditional and religious values that serve to promote health and protect biodiversity

(h) Facilitate implementation of integrated essential public health and biodiversity-related interventions for the management of both short and long-term health risks resulting from biodiversity loss and unsustainable practices;

(i) Facilitate implementation of integrated environment and health surveillance to support timely and evidence-based decisions for the effective identification and management of short and long-term risks to human health posed by ecosystem degradation and biodiversity loss by forecasting and preventing increases in related ill-health and disease

(j) Strengthen and operationalize the health components of disaster-risk reduction plans to prevent casualties resulting from the health consequences of ecosystem degradation

(k) Strengthen international and regional partnerships, joint work programs, and intersectoral collaboration on biodiversity–health linkages.

4. Towards the development of common metrics and approaches

The integration of biodiversity and human health can be facilitated by the use of common metrics and frameworks. Conventional measures of health are often too limited in focus to adequately encompass the multiple health benefits from biodiversity (Corvalan et al. 2005). Notwithstanding the broad WHO definition of health described in Chapter 2 of this volume, traditional measures of health, such as disability adjusted life years (DALYs) and burden of disease, tend to have a more narrow focus on morbidity, mortality, and disability, and fail to capture the full breadth of the complex linkages between biodiversity and health, including social and determinants and cultural underpinnings (E.g. Talbot and Verrinder 2009; see also the chapters on mental health and traditional medicine in this volume). A more holistic approach is necessary.

Examples of such tools on the human health side include environmental hazard or risk factor analyses, tools aimed at the identification (and reduction) of health disparities and inequities, identifying environmental and socio-economic determinants of disease, and conducting health impact assessments. Complementary conservation approaches include landscape and seascape change modelling, vulnerability and adaptation assessments, integrated health and environmental assessments and ecosystem service analyses. Valuation approaches, when being used in conjunction with, or being based on, tools and methods that further contribute to our understanding of ecosystem functioning and human health linkages, can also be useful tools for the assessment of benefits and trade-offs of different policy scenarios. Examples of such tools on the human health side include environmental hazard or risk factor analyses, tools aimed at the identification (and reduction) of health disparities and inequities, identifying environmental and socio-economic determinants of disease, and conducting health impact assessments. Complementary conservation approaches include landscape and seascape change modelling, vulnerability and adaptation assessments, integrated health and environmental assessments and ecosystem service analyses. Valuation approaches, when being used in conjunction with, or being based on, tools and methods that further contribute to our understanding of ecosystem functioning and human health linkages, can also be useful tools for the assessment of benefits and trade-offs of different policy scenarios.

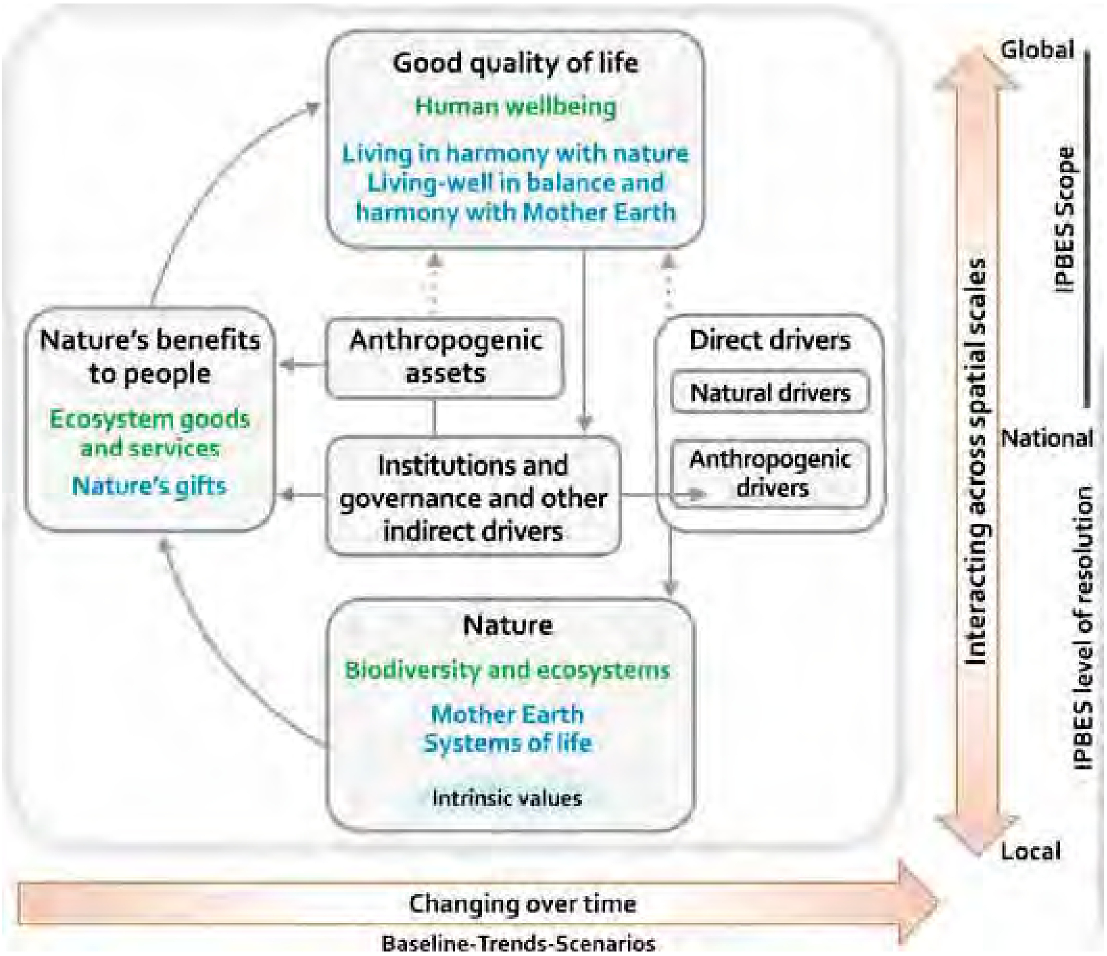
Measuring the health effects of ecosystem change by considering established "exposure" threshold values can help to highlight biodiversity-health-development linkages. Mechanisms linking ecosystem change to health effects are varied. For many sub-fields, exposure thresholds or standards have been scientifically established that serve as trigger points *for taking action* to avoid or minimize disease or disability. For example, air quality standards exist for particle pollution, WHO has established minimum quantities of per capita water required to meet basic needs, and thresholds for food security define the quantity of food required to meet individual daily nutritional needs. Measuring the health effects of ecosystem change relative to established threshold values highlights how such change constitutes exposure – an important principle linking cause and disease or other health effects – and encourages action if thresholds are exceeded.

Given the complexity and heterogeneity of the tools available to assess health and biodiversity linkages, complementary cross-sectoral approaches require the development of a common evidence base across the health and conservation sectors. These can extend from the development of standardized measures in the integration of systematic assessment processes (including environmental impact assessments, strategic environmental assessments, health impact assessments and risk or strategic assessments), to more systematic reviews of research findings, standardized data collection forms and computerized modelling programs, and the systemic consideration of multiple health impacts in policy evaluation and assessment. The integration of these tools in the development of a common framework should consider the health-biodiversity linkages – including those described throughout this volume – to manage future risks and safeguard ecosystem functioning while ensuring that social costs, associated with new measures and strategies, do not outweigh potential benefits. The development of precautionary policies and safe minimum standards that place a value on ecosystem services to health, and make positive use of linkages between biodiversity and health is critical to this endeavour. These should be considered prior to any analysis of trade-offs.

In practical terms, for example, policy-makers and researchers could prioritize measures such as integrated disease surveillance in wildlife, livestock and human populations, as a cost-effective measure to promote early detection and avoid the much greater damage and costs of disease outbreaks (see also chapter 7).

Progress toward the development of a common framework will thus require more systematic collaboration across disciplines and sectors, with greater attention being paid to "translating" the meaning of key metrics to increase their shared relevance for the health and biodiversity sectors. Similarly, frameworks provide a conceptual structure to build on for research, demonstration projects, policy and other purposes. Embracing a common framework that aims to maximize the health of ecosystems and humans both could help the different disciplines and sectors work more collaboratively. As introduced in Chapter 2 of this volume, the conceptual framework of the Intergovernmental science-policy Platform on Biodiversity and Ecosystem Services (IPBES), building upon that articulated in the Millennium

FIGURE 1: The IPBES Conceptual Framework



Source: Diaz et al 2015a.

Ecosystem Assessment, is a framework that links biodiversity to human well-being, considering also institutions and drivers of change (See Figure 1).

Fig.1 In the central panel, boxes and arrows denote the elements of nature and society that are at the main focus of the IPBES. In each of the boxes, the headlines in black are inclusive categories that should be intelligible and relevant to all stakeholders involved in IPBES and embrace the categories of western science (in green) and equivalent or similar categories according to other knowledge systems (in blue). The blue and green categories mentioned here are illustrative. Solid arrows in the main panel denote influence between elements; the dotted arrows denote links that are acknowledged as important, but are not the main focus of the Platform. The thick, coloured arrows below and to the right of the central panel indicate that the interactions between the elements change over time (horizontal bottom arrow) and occur at various scales in space (vertical arrow). Interactions across scales, including cross-scale mismatches, occur often. The vertical lines to the right of the spatial scale arrow indicate that, although IPBES assessments will be at the supranational – subregional to global – geographical scales (scope), they will in part build on properties and relationships acting at finer – national and subnational – scales (resolution, in the sense of minimum discernible unit). The resolution line does not extend all the way to the global level because, due to the heterogeneous and spatially aggregated nature of biodiversity, even the broadest global assessments will be most useful if they retain finer resolution. This figure is a simplified version of that adopted by the Second Plenary of IPBES; it retains all its essential elements but some of the detailed wording explaining each of the elements has been eliminated within the boxes to improve readability. A full description of all elements and linkages in the conceptual framework, together with examples, can be found in Diaz et al. (2015b).

5: Keeping tabs: The need for monitoring and accountability for evidence-based indicators at the intersection of biodiversity and health

Identifying ecosystems critical for the delivery of human health benefits and evaluating key socio-economic variables that affect access to and delivery of associated goods and services to communities, particularly vulnerable populations, is an instrumental step towards the identification of appropriate policy measures and strategies. However, the ongoing objective evaluation of those strategies once measures are in place, is equally essential.

Monitoring, evaluating and forecasting progress toward the achievement of national, regional and global targets at regular intervals against evidence-based indicators, including threshold values for critical ecosystem services, such as the availability and access to food, water and medicines will be essential to the effective implementation of strategies. To be effective, monitoring and evaluation will require considerable strengthening through more innovative and integrated approaches. These could include, for example, the development of robust, cross-cutting indicators that jointly address human health and environmental considerations (see, for example, Dora et al. 2014; Pelletier et al. 2014). Further guidance for the establishment of national development plans that simultaneously encourage cross-sectoral partnerships and stakeholder engagement are also critical to strengthening and encouraging more innovative monitoring and evaluation approaches.

Each of the elements identified above must be supported by the development of robust indicators. Many indicators used in biodiversity conservation and environmental management can prove useful to health impact assessments, either to help in the identification of contributing factors to existing health problems, or areas where health risks or opportunities may arise.

Drawing on the findings discussed throughout this volume, these indicators may include parameters of water quality; the extent, quality and distribution of important habitats; wildlife population movements; animal and plant health status; and various indicators of biodiversity loss. Similarly, in some circumstances the indicators used by the health community (nutritional status and availability, births, deaths, morbidity, occurrence of specific diseases, etc.) may help to bring specific ecological issues into focus or help identify areas in which conservation measures need to be assessed, strengthened or revised. The same holds true for the development sector, since the delivery of ecosystem services are supported by biodiversity. Inter-disciplinary partnerships to identify existing indicators which can be used directly or modified to address cross-cutting issues are an important element of capacity building for the ecosystem approach, and help to promote co-operation. Examples of cross-cutting indicators which might be considered are provided in Table 2 below.

6. Assessing the economic value of biodiversity and health: benefits and limitations

Providing estimated economic values for an ecosystem service can be useful for internalizing that value and guiding decision-making and more integrated policy analysis. If used effectively, and in conjunction with other tools, some valuation approaches can help us reconsider our relationship with the natural environment, alerting us to the consequences of our choices and behaviour for the environment and human health. Translating the value of natural resources and costs associated with conservation into economic terms can promote more equitable, effective and efficient conservation practices, help to identify more efficient means of delivering ecosystem services, identify more cost-effective alternatives, and allow for a more thorough assessment of trade-offs (TEEB 2010). Significantly, some aspects of ecosystem functioning such as ecological *resilience* cannot be fully captured in quantitative valuations. However, in most cases, economic values can be presented as complementary information, thus contributing to the overall calculation.

Valuation approaches linking ecosystem functioning and health that support decisions about resource allocation may appeal to a variety of stakeholders, including many of those in the public health and conservation sectors. Many tools for monetary valuation of ecosystem services have been developed in recent decades (for a recent review see e.g. Brouwer et al. 2013; for different approaches see also see also Gómez-Baggethun et al. 2014; Nelson et al. 2009; Brauman et al. 2007; Costanza et al 2006; Nunes et al. 2001). The Economics of Ecosystems and Biodiversity (TEEB), a global multidisciplinary initiative that seeks to mainstream the value of biodiversity and ecosystem services, has been particularly successful in drawing attention to the global economic benefits associated with biodiversity conservation and the growing financial ecological and human burden associated with its loss (http://www.teebweb.org) (MacDonald and Corson 2012).

People rely on a range of ecosystem services to sustain livelihoods, health, and well-being, of which only a subset can be reflected in economic evaluations in monetary terms; still fewer can be addressed through market-based instruments. The Economics of Ecosystems and Biodiversity (TEEB) follows a tiered approach in analyzing and structuring valuation, including: societal recognition of values; demonstration value in economic terms where possible; and in some cases, using market-based mechanisms to capture value. The TEEB initiative calls for the internalization and assessment of values of biodiversity and ecosystem services where it can practically and appropriately be carried out, based on the recognition that it is unacceptable "…*to permit the continued absence of value to seep further into human consciousness and behaviour, as an effective 'zero' price, thus continuing the distortions that drive false trade-offs and the self-destructiveness that has traditionally marked our relationship with nature*" (TEEB 2010:12).

The approach also acknowledges several of the limitations, risks and complexities involved in

Table 2: Examples of cross-cutting indicators[1]

Issue	Cross-cutting indicators
Water and air quality	• Biological/health hazards of source water from different sectors (e.g. agriculture; mining; energy development) • Chemical integrity of source water (e.g. pesticides, endocrine disrupting compounds, and harmful algal blooms (cyanotoxins). • Shifts in lychen species (as an indicator for air quality)
Food security, nutrition, and noncommunicable diseases	• Nutritional status (e.g. type and prevalence of nutrient deficiencies) • Food species diversity • Status of unmanaged agrobiodiversity (e.g. pollinators, pests, predators) • Time spent / distance travelled accessing foods • Income and dietary intake from traditional foods, including wild foods • Land used for producing traditional foods • Prevalence of malnutrition / diet-related non-communicable disease • Food yields from various resources (e.g. crops, fish/aquaculture, hunting) • Outbreaks of food-borne disease • Land use change (e.g. % area, pace of change, intensification) • Use of agrobiodiversity in healthcare interventions (e.g. intervention type, species used)
Infectious diseases	• Areas of intact habitat in high risk areas • Status of wildlife populations (distribution, movement, abundance, diversity, conservation status) • Outbreaks of zoonotic, water-borne, vector-borne and food-borne disease (frequency, distribution, morbidity, mortality) • Outbreaks of human / wildlife / livestock / plant disease • Water availability, vulnerability and quality • Land use change (e.g. % area, pace of change, intensification) • Outbreaks of infectious human/wildlife/livestock disease
Medicinal resources	• Use of biodiversity for primary medicinal resources (e.g. % of total medicinal use, % income derived from sale of traditional medicines) • Status of key species and related habitats • indigenous population indicators – movements, density, births, morbidity and mortality
Disaster risk and climate change	• Areas of intact habitat in high risk areas • Encroachment and degradation (e.g. wetland reclamation, deforestation, urban sprawl) • Population density in high risk areas • Dependence of population on local ecosystems for food / medicine / income (e.g. % of total population, income derived from ecosystems etc) • Area of land experiencing erosion, deforestation, drought, desertification • Frequency and severity of disasters • Population displaced by disasters, and degree / pace of return • Prevalence of disease after disasters • Land use change (% area, pace of change, intensification) • Indicators of climate adaptation and mitigation measures implemented by other sectors on biodiversity and human health

[1] Adapted from COHAB Initiative, unpublished.

economic valuation, covers different types of value appreciation, and includes various categories of response at the level of public policies, voluntary mechanisms and markets (Box 1).

Capturing the full range of values associated with biodiversity loss, including socio-cultural dimensions, requires that economic valuation tools are complemented with non-monetary valuation methods and planning tools based on various (cross-sectoral) criteria that help to differentiate benefits and trade-offs. The development of frameworks of this kind involve synthesizing the abundant but often scattered body of literature that analyses non-monetary values of biodiversity, and articulating it into ecosystem service concepts, methods, and classifications (Gómez-Baggethun and Muradian 2015; Kelemen et al. 2014; Christie et al. 2012; Gimona and van der Horst 2007). TEEB is clearly a useful framework that has been put to widespread use around the globe, but further strengthening of the health dimensions of valuation are also needed.

Box 1: The TEEB approach

Recognizing Value: Recognizing value in ecosystems, landscapes, species and other aspects of biodiversity is a feature of all human societies, and is sometimes sufficient to ensure conservation and sustainable use. This may be the case especially where the spiritual or cultural values of nature are strong. For example, protected areas such as national parks have historically been established in response to a sense of collective heritage or patrimony, a perception of shared cultural or social value being placed on treasured landscapes, charismatic species or natural wonders. Protective legislation or voluntary agreements can be appropriate responses where biodiversity values are generally recognized and accepted. In such circumstances, monetary valuation of biodiversity and ecosystem services may be unnecessary, or even counterproductive if it is seen as contrary to cultural norms or fails to reflect a plurality of values.

Demonstrating Value: Demonstrating value in economic terms is sometimes useful for policymakers and others, in reaching decisions that consider the full costs and benefits of a proposed use of an ecosystem, rather than only costs or values that enter markets in the form of private goods. *Economic valuations* of natural areas are a case in point. Examples include calculating the costs and benefits of conserving the ecosystem services provided by wetlands in treating human wastes and controlling floods, compared to the cost of providing the same services by building water treatment facilities or concrete flood defences. Valuation is best applied for assessing the consequences of changes resulting from alternative management options, rather than attempting to estimate the total value of ecosystems. Most valuation studies do not assess the full range of ecosystem services and not all biodiversity values can be reliably estimated using existing methods. The identification of all significant changes in ecosystem services is a necessary first step even if all of them are not monetized.

Capturing Value: This final tier involves the introduction of mechanisms that incorporate the values of ecosystems into decision-making, through incentives and price signals. This can include payments for ecosystem services, reforming environmentally harmful subsidies, introducing tax breaks for conservation, or creating new markets for sustainably produced goods and ecosystem services. It needs to come along with reinforcing rights over natural resources and liability for environmental damage. The challenge for decision makers is to assess when market-based solutions to biodiversity loss are likely to be culturally acceptable, as well as effective, efficient and equitable.

Source: TEEB, 2010

7. Shaping behaviour and engaging communities for transformational change

Human behaviour is central to the biodiversity-human health nexus: our actions, as producers and consumers of energy, natural resources and manufactured products, are prime determinants of both the ability to conserve biodiversity and to promote human health. Therefore, managing, and benefiting from, the interlinkages between biodiversity, ecosystems services and human health increasingly demands broad-scale interventions that effectively and sustainably influence human behaviour (Freya et al. 2010; Fulton et al. 2011; The Lancet 2015).

The social sciences can assist us to motivate choices consistent with health and biodiversity objectives and to develop new approaches through, inter alia, better understanding of behavioural change, production and consumption patterns, policy development, and the use of non-market tools (CBD 2013a). Accordingly, the development of work on values, institutions and behaviour is needed (CBD 2013b; Duraiappah et al 2014).[2] It has been argued that intervention efforts that also seek to modify the physical, social, political, and economic environments in which people live and make health and environment related decisions can jointly deliver health, environmental and social benefits (e.g. Allegrande 2015 and references therein; Pons-Vigués et al. 2014).[3] Core elements to promote behaviour change on a global scale include:

i) Understanding the drivers of human behaviour and the role of micro- and macro-level processes (including political, social, environmental and economic institutions and structures) in mediating positive change;

ii) Recognizing that influencing human behaviour can take many forms but that strategies should be tailored to specific contexts and issues; and

iii) Addressing the significant gap in knowledge on what works, how and why, in order to develop evidence-based best practices that can be scaled-up for sustainability.

Tackling these and other aspects of human behaviour change can have far-reaching implications for poverty alleviation, human health and biodiversity conservation (Allegrante 2015; Barrett et al. 2011). Each of these is relevant to building a culture of health that is in line with social and environmental objectives, including those embedded in the Strategic Plan for Biodiversity 2011–2020 and its Aichi biodiversity targets, and the emerging sustainable development goals.

Understanding the drivers of human behaviour requires moving beyond rational individualistic behaviour models in order to appreciate the complexities of daily life, social and economic incentives for change, and actual processes of change (Hargreaves 2011; Pons-Vigués et al. 2014). Social, cultural and psychological factors interact in complex ways with broader economic, political and environmental processes (Marmot et al. 2008; Waylen et al. 2010). Designing effective and sustainable behaviour change interventions also demands that we account for the perceptions, needs, capacities, heterogeneity and constraints of communities. Engaging with human behaviour change also involves understanding complexity at different scales, which requires multi-disciplinary approaches. In addition to the need to further strengthen the scientific base of a broad range of issues at the intersect of biodiversity and health, there is also a need for policymakers and practitioners to draw deeply from the social sciences (psychology, anthropology, sociology, political science and other fields) in order to inform strategies (Glanz and Bishop 2010). Moreover, the traditional values of indigenous and local communities can sometimes provide critical foundations for positive behaviour change; recognizing these values and working with these groups to develop more sustainable production

[2] UNEP/CBD/SBSTTA/17/INF/1

[3] The effectiveness of such approaches in addressing ethical considerations or reducing health disparities has also been questioned (Lieberman et al. 2013).

and consumption patterns is essential (Kuhnlein et al. 2013).[4]

In addition, the importance of behavioural change in the private and business sectors is also critical to achieving truly sustainable development, as many of the goals and targets at the biodiversity and human health nexus require encouraging the private sector to adopt more sustainable practices (e.g. supply chain management).

With reference to any particular set of objectives, behaviour change includes efforts (such as modifying institutional or social structures) to reduce behaviours that are negative to the objectives, promote behaviours that are positive, and increase structural determinants so as to foster "nurturing environments" (Biglan et al. 2012). Interventions can be very broadly divided into top-down and bottom-up approaches. These can take many forms and make use of different strategies, ranging from media campaigns, promoting the adoption of specific technologies, fostering compliance and/or community dialogue on regulatory policies and legislative reforms, strengthening community action, building local resilience, and many others (Gaventa and Barrett 2012). Whatever the approach, it is important that interventions be tailored to local, social, cultural, economic, political and environmental contexts in order that strategies consider local constraints, values and incentives for change (Wakefield et al. 2010; Netto et al. 2010). However, it is not enough that behaviour change programmes be culturally-acceptable; they also need to be based on a compelling rationale for change (see Panker-Brick et al. (2006) for malaria prevention; Moon and Cocklin (2013) for biodiversity conservation; Sunderlin (2006) for forest conservation; Lewis et al. (2011) for sustainable agriculture; Newson et al. (2013) for nutrition; and Vaughan et al. (2013) for safe drinking water).

Many large-scale programmes for behavioural change are often poorly implemented and rely solely on passive information dissemination that excludes sufficient recognition of related structural barriers (political, social and environmental) and of efforts to address them (Lieberman et al. 2013; Khun and Manderson, 2007). Strategies for the conservation and sustainable use of biodiversity, including through the CBD, commonly focus on promoting changes in awareness, with the assumption that changes in these indicators will precede behaviour change. Unfortunately, as noted by Verissimo (2013), this assumption is generally wrong (McKenzie-Mohr et al. 2011). The same can be said of interventions in the health sector which often focus on "downstream" drivers of health (Freudenberg et al. 2015; WHO 2008; Marmot et al. 2008; Freudenberg et al. 2015) rather than "upstream" drivers such as biodiversity loss (WHO 2012) and *individual* behaviour modification strategies rather than modifying the social, political, economic and physical environments in which people live (Golden and Earp 2012; Pons-Vigués et al. 2014).

There are a variety of innovative techniques that can be used to move beyond didactic methods in order to engage with community participation, skills development and the addressing of broader social determinants (Trickett et al. 2011), such as developing or reformulating technologies as agents of behaviour change (Newson et al. 2013), social marketing (McKenzie-Mohr et al. 2011), school-based programmes that combine education and environmental interventions (De Bourdeaudhuij et al. 2011), and social mobilization (Pretty et al. 2002). These examples show the need for interventions to engage in innovation, embracing both complexity, and long-term visions of change, which in turn rely on sufficient resource-mobilization.

The health sector can provide useful experience in this regard. Social marketing has been widely implemented in the health sector in countries with promising results in addressing issues such as obesity and smoking (French et al. 2009; Shin et al. 2015; Gielen and Green 2015). Social marketing consists of a suite of research and

[4] For example, Kuhnlein et al. (2013) discuss how the Ainu people in the Saru River region, Japan, approached behaviour change. In chapter 14 of that same volume detailed approaches and methods for behaviour change among indigenous peoples are also discussed.

execution techniques; this is the application of marketing concepts and techniques, informed by the psychology of persuasion and influence to create, communicate and deliver values to influence behaviour and benefit the target audience and society (Kotler & Lee 2011). It also involves the development of non-traditional partnerships. For example, as Shin and colleagues (2015) demonstrate, developing unique cross-sectoral partnerships by combining health sector information with point-of-purchase strategies can also encourage positive behaviours that jointly promote healthy foods and make them more accessible, including among low-income populations which can, in turn, contribute to a reduction in obesity rates.

8. Research needs

As the various chapters in this volume have demonstrated, scientific data and information from multiple sources and disciplines are not only fundamental to our understanding of biodiversity-health linkages but to the identification of more integrated public health, conservation and development strategies. While this knowledge is increasing rapidly, many data gaps persist and much more sustained cross-disciplinary research is needed to evaluate the full-breadth of these complexities across geographical and temporal scales (for recent discussion on existing research gaps see also, for example, Myers et al. 2013; Sandifer et al. 2015).

Further research is needed to elucidate some of the potential knowledge gaps on linkages between biodiversity and human health. For example, key questions include:

a. What are the relationships between biodiversity, biodiversity change and infectious diseases? Specifically, what are the effects of species diversity, disturbance and human-wildlife contacts? What are the best metrics by which to measure exposure?

b. What role does functional diversity play? How might it modulate health outcomes? What are the implications for spatial planning?

c. What are the linkages between biodiversity (including biodiversity in the food production system), dietary diversity and health? Is there a relationship between dietary biodiversity and the composition and diversity of the human microbiome? What are good indicators of dietary biodiversity? What are the linkages between biodiversity in environment, the human microbiome and health?

d. Beyond microbial influences on the immune system, what are the actual mechanisms by which exposure to biodiverse environments influence health outcomes? What are the implications for the design of buildings and cities and access to "natural environments"? What are the implications for the treatment of some non-communicable diseases? What are the cumulative health impacts of ecosystem alteration? Who stands to benefit?

e. Beyond provisioning services, which components of coastal and marine ecosystems lead to positive human health outcomes? Does exposure to marine biodiversity have measurable health benefits?

f. How can biodiversity monitoring be better integrated with or more accessible to the public health and conservation communities?

These and many other questions merit further attention from the scientific community in order for science to more meaningfully inform policy and decision-making. Ensuring that this knowledge can also be accessed and shared by decision-makers and practitioners, including among and between low- and middle-income countries, is not only instrumental to their wide-scale implementation but to the operationalization of our shared commitment to achieve sustainable development objectives (Sachs 2012).

The knowledge in question must not be confined to scientific data nor any single discipline, as multiple sources of information are critical to understanding the direct threats to and underlying drivers of ill health and biodiversity loss. For example, further research is needed to assess the current proportion of species used for medicinal and food purposes; qualitative data is also needed to determine the proportion of this reliance on natural resources that is based on needs and that which is based on individual preferences. This research can in turn be critical to developing sound strategies aimed at sustainable use, management and trade of biological resources essential to human health and well-being.

Considering the regional heterogeneity of the disease burden, and the variation of interactions between variables at different scales, analyses of local burdens of disease (including the eventual implementation of sustainable development goals and targets in the post-2015 period) should be complemented by strategies that also take local variability into account (Murray et al. 2012). Findings from the natural sciences should be complemented by work from numerous other disciplines, including the social sciences. The latter are especially relevant to behavioural change discussed in the previous section. Analyses should also draw from local knowledge ensuring, insofar as possible, full and effective participation of local and community-level stakeholders. This routinized participation will not only contribute to strengthening and/or validating scientific knowledge, but also increase opportunities for mutual learning, transparency, coherence and collaboration. By its very definition, mainstreaming (biodiversity considerations) implies that the integration of biodiversity in relevant public and global health policies and strategies will require the involvement of various stakeholders, at multiple scales.

9. Integrating biodiversity and health into the sustainable development agenda

"We reaffirm the intrinsic value of biological diversity, as well as the ecological, genetic, social, economic, scientific, educational, cultural, recreational and aesthetic values of biological diversity and its critical role in maintaining ecosystems that provide essential services, which are critical foundations for sustainable development and human well-being. We recognize the severity of the global loss of biodiversity and the degradation of ecosystems and emphasize that these undermine global development, affecting food security and nutrition, the provision of and access to water and the health of the rural poor and of people worldwide, including present and future generations..." (UN, The Future We Want, 2012).

The United Nations Conference on Sustainable Development (UNCSD, Rio+20), in its outcome document, "The future we want", agreed to establish a process to develop sustainable development goals (SDGs) as a key part of the United Nations development agenda beyond 2015. Human health, biodiversity and ecosystems were all prominently featured in the outcome document which devoted numerous paragraphs to calls for a comprehensive framework for a healthy, sustainable and more equitable future (UN, 2012). The need to eradicate poverty and to further mainstream sustainable development at all levels was recognized from the outset as was "integrating economic, social and environmental aspects and recognizing their interlinkages, so as to achieve sustainable development in *all* its dimensions" (UN 2012: paragraph 3).

The SDGs are intended to build upon the Millennium Development Goals (MDGs), which were an expression of the international community's commitment to global development, bringing social dimensions such as environment, poverty, hunger, disease, education, and gender equity to the forefront of the global policy agenda. The MDGs and their associates 2015 targets were largely successful in giving new prominence to global public health issues affecting poor and vulnerable populations (Sachs 2012; Smith and Taylor 2013). The health-related MDGs have contributed to reinvigorating several multilateral health institutions (although global engagement could be much more effective and coordinated); galvanized collective action in the fight against HIV-AIDS, contributing to the expansion of coverage with antiretroviral drugs (despite a large – and ongoing- access gap); contributed to an overall reduction of deaths from malaria, tuberculosis and some other infectious diseases; contributed to an increase in overall access to immunizations in developing countries and reduced child mortality (Carlsson and Nordström, 2012). The MDG framework included the biodiversity target to “reduce biodiversity loss, achieving, by 2010, a significant reduction in the rate of loss, 5 under Goal 7 “ensuring environmental sustainability”. The target originated from the “2010 biodiversity target”, adopted, in 2002, by the Conference of the Parties to the Convention on Biological Diversity and also by the World Summit on Sustainable Development, as part of the Johannesburg Plan of Implementation.

While biodiversity and environmental sustainability more generally, were included in the MDG framework, in the implementation of the framework, the importance of biodiversity for the achievement of the other MDGs (including the high-profile goals on poverty, food, and health) was not sufficiently recognized. Despite many actions in support of biodiversity, the 2010 biodiversity target was not fully met because the actions were not taken on sufficient scale and because the underlying drivers of loss were not addressed significantly. In the post-2015 development agenda, biodiversity needs to be better integrated into broader development objectives (CBD 2013a).

In line with the mandate from Rio+20, United Nations General Assembly established an Open Working Group on Sustainable Development Goals and tasked it to prepare a proposal for the SDGs. The Group has proposed 17 goals (see Table 3). The SDGs are due to be finalized and adopted by the United Nations General Assembly in September 2015.

While one of the proposed goals is focussed specifically on human health (Table 3) others also address important and closely-related components of human well-being including the eradication of poverty, food security and nutrition, availability of water and sanitation, and access to modern energy. Biodiversity is related to each of these components and these intersections have been demonstrated at length throughout this volume. Biodiversity is addressed explicitly in two of the proposed goals and in several sub-targets including those related to food and water. The proposed goals also recognize the importance of sustainable consumption and production, as well as the importance of gender equality and equity.

Indeed, the sustainable development framework must not only acknowledge the role of biodiversity for its contribution to development, but also provide the enabling conditions for its conservation and sustainable use by promoting ***transformational change*** in economies and societies. This not only requires improving governance, considerably strengthening institutional and cross-sectoral collaboration at multiple scales, and coordinating global responses, it also demands behavioural change and building human capabilities through access to education and health care (CBD 2013b).

Within the SDG process, unique opportunities to advance the parallel goals of improving health and other social dimensions of sustainable development can be maximized by harnessing opportunities that deliver joint benefits, such as measures and policies at the intersection of nutrition, urban health, and noncommunicable diseases (see chapter 6).

In line with the rationale and methods proposed by Dora and colleagues (2014), progress toward intersecting goals could be measured against a robust set of target indicators that evaluate health-related-risks modulated by biodiversity-related measures. For example, target indicators could be developed to evaluate progress of actions taken based on sustainable food production and agriculture polices (see chapter 5) that could not only contribute to biodiversity protection and ecosystem resilience but also improve human nutrition (under SDG goal 2), and contribute to reducing the burden of noncommunicable diseases (under SDG goal 3). The SDG framework should additionally provide for the enabling conditions for human health and for the conservation and sustainable use of biodiversity, and for the underlying drivers of biodiversity loss and ill health to be addressed (Chapter 2). This further implies Goals for improved governance, and institutions, at appropriate scales (from local to global), for the management of risks and the negotiation of trade-offs among stakeholder groups, where they are necessary.

As national policies and strategies continue to develop, the ongoing evaluation of synergistic and

Table 3[5]: Summary of the sustainable development goals and targets proposed by the open working group on sustainable development goals, and how biodiversity, and elements of the Strategic Plan for Biodiversity 2011–2020, are addressed by them

The proposed sustainable development goals (SDGs)	Biodiversity addressed in targets	
	Directly	**Indirectly**
End poverty in all its forms everywhere		Targets 1.4; 1.5; 1.a; 1.b
End hunger, achieve food security and improved nutrition, and promote sustainable agriculture	Targets 2.4; 2.5	Targets 2.1; 2.3; 2.a; 2.b
Ensure healthy lives and promote well-being for all at all ages		Targets 3.3; 3.4; 3.8; 3.9; 3.b; 3.d
Ensure inclusive and equitable quality education and promote life-long learning opportunities for all		Targets 4.5; 4.7
Achieve gender equality and empower all women and girls		Targets 5.1; 5.5; 5.a; 5.c
Ensure availability and sustainable management of water and sanitation for all	Target 6.6	Targets 6.1; 6.3; 6.4; 6.5; 6.a, 6.b
Ensure access to affordable, reliable, sustainable, and modern energy for all		Target 7.a
Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all	Target 8.4	Targets 8.2; 8.3; 8.5; 8.9
Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation		Targets 9.1; 9.4; 9.a; 9.b
Reduce inequality within and among countries		Targets 10.2–10.4; 10.a; 10.b
Make cities and human settlements inclusive, safe, resilient and sustainable	Targets 11.4; 11.7; 11.a	Targets 11.1; 11.3; 11.5; 11.6; 11.b; 11.c
Ensure sustainable consumption and production patterns	Targets 12.2; 12.4; 12.8	Targets 12.1; 12.5; 12.7; 12.a; 12.b
Take urgent action to combat climate change and its impacts		Targets 13.1–13.3; 13.a; 13.b
Conserve and sustainably use the oceans, seas and marine resources for sustainable development	Targets 14.1–14.6; 14.c	Targets 14.7; 14.a; 14.b
Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss	Targets 15.1–15.9; 15.a-15.c	
Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels		Targets 16.3; 16.4; 16.6; 16.7; 16.8; 16.10; 16a; 16.b
Strengthen the means of implementation and revitalize the global partnership for sustainable development		Targets 17.2–17.4; 17.6-17.11; 17.14–17.19

[5] From Progress report on the process of integrating biodiversity into the post-2015 framework for sustainable development (UNEP/CBD/COP/12/15)

antagonistic effects of complementary sustainable development goals and targets will be essential. This includes sustainable development goals and targets addressing health, food and freshwater security, climate change and biodiversity loss. Consistent evaluations of the long-term impacts of trade-offs are also needed. For example, the short-term gains from intensive and unsustainable agricultural production must be weighed against costs to longer-term nutritional security; the impacts of unsustainable agricultural practices that may exacerbate climatic pressures may also lead to greater food insecurity, particularly among poor and vulnerable populations, by negatively influencing food availability, accessibility, utilization and sustainability.

As with other global policy developments, the SDGs present many opportunities for the realization of many of the key messages that derive from this State of Knowledge Review. It will be up to the biodiversity conservation and human health communities to help shepherd related national policies in the most rewarding directions.

Conclusion

Health is our most basic human right and one of the most important indicators of sustainable development. At the same time, as the chapters throughout this volume have shown, the conservation and sustainable use of biodiversity is imperative for the continued functioning of ecosystems at all scales, and for the delivery of ecosystem services that are essential for human health. There are many opportunities for synergistic approaches that promote both biodiversity conservation and the health of humans. In some cases there must be trade-offs among these objectives. Indeed, because of the complexity of interactions among the components of biodiversity at various tropical levels (including parasites and symbionts), and across ecosystems at various scales (from the planetary-scale biomes to human-microbial interactions), positive, negative and neutral links are quite likely to occur simultaneously. An enhanced understanding of health–biodiversity relationships will allow for the adjustment of interventions in both sectors, with a view to promoting human well-being over the long-term.

Integrating linkages at the biodiversity–health nexus in public health, conservation and sustainability strategies will contribute not only to improved health and biodiversity outcomes but also to poverty alleviation, disaster-risk reduction, and sustainable development more broadly in line with the goals of the emerging post-2015 development agenda (Horwitz et al. 2012; Langlois et al. 2012; Romanelli, 2014b). Both the SDGs and the objectives of the CBD Strategic Plan 2011–2020 will require adequate levels of resource commitment, citizen action, professional development, capacity building, and other factors, but what is most needed overall is a fundamental shift in how western societies tend to view nature as separate from human values and needs.

This volume has identified numerous linkages between human health, ecosystem services, and biodiversity. While there remain serious gaps in knowledge and the need for deep policy innovations persists, we can look with cautious optimism toward the near future as our scientific knowledge base increases and our understanding of these complex linkages unfolds. In turn, political pressure to move toward sophisticated, integrated policy design will only increase as public awareness and anxiety over the immense costs of inaction grows. In this light, connecting the global priorities of biodiversity and health is not only prudent; it is a form of long-term insurance for community resilience and the well-being of future generations.

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Chapter 1 and 2

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Chapter 6

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Chapter 7

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Chapter 8

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United Nations Decade on Biodiversity

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