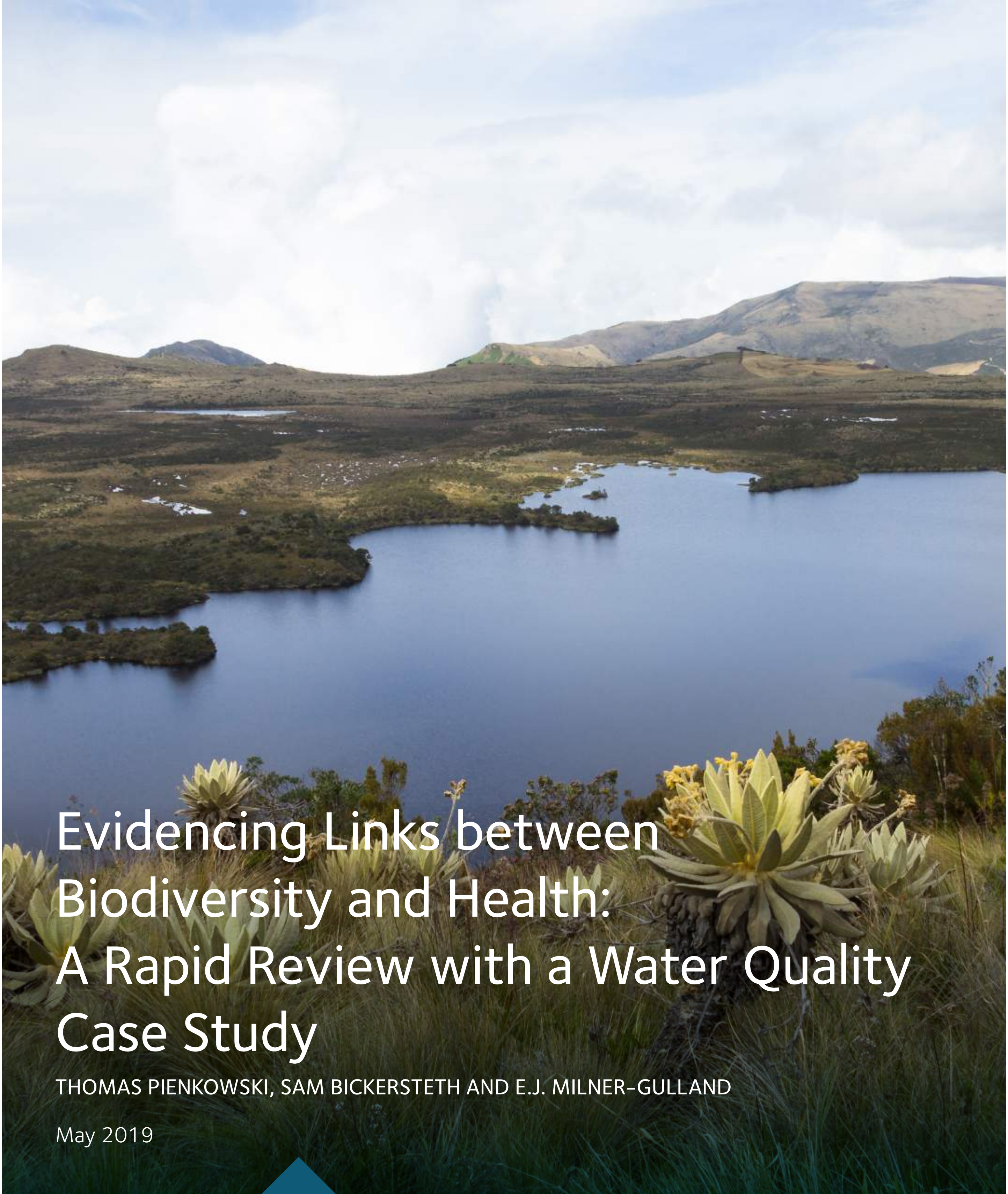

Evidencing Links between Biodiversity and Health: A Rapid Review with a Water Quality Case Study

THOMAS PIENKOWSKI, SAM BICKERSTETH AND E.J. MILNER-GULLAND

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The ROCKEFELLER FOUNDATION

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Evidencing Links between Biodiversity and Health: A Rapid Review with a Water Quality Case Study

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Cover image: Páramo landscape, Colombia (Adobe Stock)

Introduction to Planetary Health

Planetary health is a multi-disciplinary approach that addresses the interconnections between the processes of environmental change and their impacts on human health and well-being, at scale. The planetary health concept builds on the ecological framing of planetary boundaries and supports the UN Sustainable Development Goals and the Paris Climate Change Agreement, both of which recognize the importance of regional and global coordination to solve complex environmental and development challenges.

Links between environmental change and human health are both direct (e.g. impact of air pollution on respiratory and cardiac functioning) and indirect (e.g. extreme weather events or sea-level rise leading to permanent displacement) but there is plausible connection between the change in natural systems and human well-being. The planetary health approach requires transboundary perspectives covering issues that one country cannot address in isolation. Solutions, however, may be local, national, regional or international.

The work of The Rockefeller Foundation Economic Council on Planetary Health, through its Secretariat based at the Oxford Martin School at the University of Oxford, aims to provide a policy-oriented, economic perspective to developing solutions. The central economic concept is that externalities – or costs and benefits to another party that are not priced, regulated or consented to – should better address planetary boundaries than at present. The analysis pays attention to equity and distributional issues, recognising how different people, institutions, countries and trajectories of development are affected by the impact of planetary health and the measures proposed to address it. This work seeks to target recommendations at global and national policy-makers.

A series of background papers has been developed by the Secretariat. These papers aim to illustrate where solutions might be identified and applied, diagnosing planetary health issues by highlighting drivers of change, significant environmental impacts and the resulting human health impacts.

This paper explores the links between biodiversity and human health, proposing a conceptual framework to understand these links, and to manage the uncertainty that arises from the complexity of biodiversity-health links and the associated knowledge gaps. It then tests and populates the proposed framework with the example of water quality regulation. Through this approach, the paper provides valuable recommendations and guidance to policymakers and technical experts, including those developing international biodiversity and health targets.

Sam Bickersteth
Executive Director, The Rockefeller Foundation Economic Council on Planetary Health

The full set of papers can be accessed at: *www.planetaryhealth.ox.ac.uk/publications*.

Glossary

Biodiversity: "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" (UN 1992)

Capital: "anything which can, either directly or indirectly, yield flows of value to people over time" (Dickie et al. 2014)

Ecosystem service: "the benefits people obtain from ecosystems" (MA 2003)

Ecosystem: "a dynamic complex of plant, animal and micro-organism communities and their non-living environment interacting as a functional unit" (UN 1992)

Functional diversity: "the distribution and the range of what organisms do in communities and ecosystems" (Schleuter et al. 2010)

Genetic diversity: "the variation in the amount of genetic information within and among individuals of a population, a species, an assemblage, or a community" (UN 1992b)

Health: "a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity" (WHO 1946)

Mental health: "a state of well-being in which the 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 his or her community" (WHO 2001)

Natural capital: "a configuration (over time and space) of natural resources and ecological processes, that contributes through its existence and/or in some combination, to human welfare" (Dickie et al. 2014)

Physical health: "the absence of detectable disorder"(Murray et al. 1982) or being "capable of "allostasis"—the maintenance of physiological homoeostasis through changing circumstances" (Huber et al. 2011)

Social health: "that dimension of an individual's well-being that concerns how [they get] along with other people, how other people react to [them], and how [they interact] with social institutions and societal mores" (Russell 1973)

Socio-ecological system: "complex adaptive systems with key characteristics such as: (1) integrated biogeophysical and socio-cultural processes, (2) self- organization, (3) nonlinear and unpredictable dynamics, (4) feedback between social and ecological processes, (5) changing behavior in space (spatial thresholds) and time (time thresholds), (6) legacy behavioral effects with outcomes at very different time scales, (7) emergent properties, and (8) the impossibility to extrapolate the information from one SES to another" (Delgado-Serrano et al. 2015)

Species diversity: "biodiversity at the species level, often combining aspects of species richness, their relative abundance, and their dissimilarity" (Hassan et al. 2005)

Stocks: Assets that can be considered as sub-units of capital (Mace and Bateman 2018)

Well-being: "a perspective on a good life that comprises access to basic materials for a good life, freedom and choice, health and physical well-being, good social relations, security, peace of mind and spiritual experience" (Pascual et al. 2017)

Executive Summary

There is an increasing awareness that human health is connected to the state of the natural world, which includes the earth's biological diversity. This awareness is reflected in efforts to align intergovernmental biodiversity and health targets. Yet, the links between biodiversity and human health are complex and poorly understood. This uncertainty may create challenges for policy-making at the interface between health and biodiversity.

We offer a conceptual framework to help identify gaps in understanding as the first step in managing this uncertainty. We then populate the conceptual framework with the example of water quality regulation, an important ecosystem service. We choose to focus on water quality because of the high morbidity associated with waterborne diseases and the relative availability of research studies addressing this issue. Finally, we highlight and build upon a number of existing policy recommendations in light of this review, which we target at technical audiences involved in developing global biodiversity and health targets.

We find that the role of biodiversity in supporting ecosystem processes is well evidenced in general, and for our specific case study, some evidence exists that biodiversity enhances water quality. We find no empirical estimates of the health burden attributable to changing water quality as the result of biodiversity changes. However, habitat, which can co-vary with biodiversity, may affect water quality; some correlative evidence suggests that higher upstream forest cover is associated with a lower risk of diarrhoeal illness in populations sensitive to surface water quality. Furthermore, upstream watershed degradation is associated with higher downstream water treatment costs; in some cases, there may be positive returns on investment to watershed conservation. Yet, it remains unclear to what degree water quality services are determined by biodiversity relative to other ecological processes, rather than simply resulting from lower rates of pollution in more biodiverse areas. There is also little evidence of how the links between biodiversity and health, through water quality, are mediated by social, economic, behavioural and technological factors. Additionally, studies generally focus on physical health, largely neglecting mental and social aspects.

We suggest that technical audiences involved in developing international biodiversity and health targets may seek to:

- Raise awareness among policy-makers, business leaders and civil society organisations of the potential links between biodiversity and health, and the need for precautionary and "no regrets" approaches.
- Encourage governments and business to refine health and environmental monitoring systems and indicators and integrate them into evidence-based decision-making.
- Highlight the need for applied research to understand the links between health and biodiversity better.

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1. Introduction

Enhancing well-being is increasingly seen as the ultimate objective of government policy, with health being a key contributor to people's quality of life (OECD 2017; Office for National Statistics 2018; WHO 2018). Yet, there is growing concern that human-caused changes to earth systems may create new threats to human health (Whitmee *et al.* 2015; Myers 2017). In particular, there is an increasing understanding that ecological systems and human health are connected (e.g. UN 2017). For example, the sixth UN flagship *Global Environment Outlook* report, published in March 2019, states "a healthy planet is a necessary foundation for human physical, psychological, social, economic and emotional health and well-being, and is therefore critical for achieving all the SDGs" (UNEP 2019). Similarly, a joint UN Convention on Biological Diversity (CBD) and World Health Organisation statement says "biodiversity underpins ecosystem functioning and the provision of goods and services that are essential to human health and well-being" (CBD and WHO 2015).

Many global environmental targets now recognise the links between biodiversity and human well-being, which can include health. For instance, the *Strategic Plan for Biodiversity* 2050 Vision states that "biodiversity is valued, conserved, restored and wisely used, maintaining ecosystem services, sustaining a healthy planet and delivering benefits essential for all people" (CBD 2018a). To help realise this vision, the United Nations Development Programme (UNDP) and the CBD have aligned the 2030 Sustainable Development Goals (SDG) and Aichi Biodiversity Targets. This includes, for example, explicitly linking SDG 3 (ensuring healthy lives for all) with Aichi target 14 (protecting biodiversity and associated ecosystem services that contribute benefits to people) (CBD *et al.* 2016). Looking forward, health is likely to feature in the target replacing Aichi 14 within the post-2020 biodiversity framework, making this an opportune time to assess the strength of the evidence linking biodiversity and health (IUCN 2018).

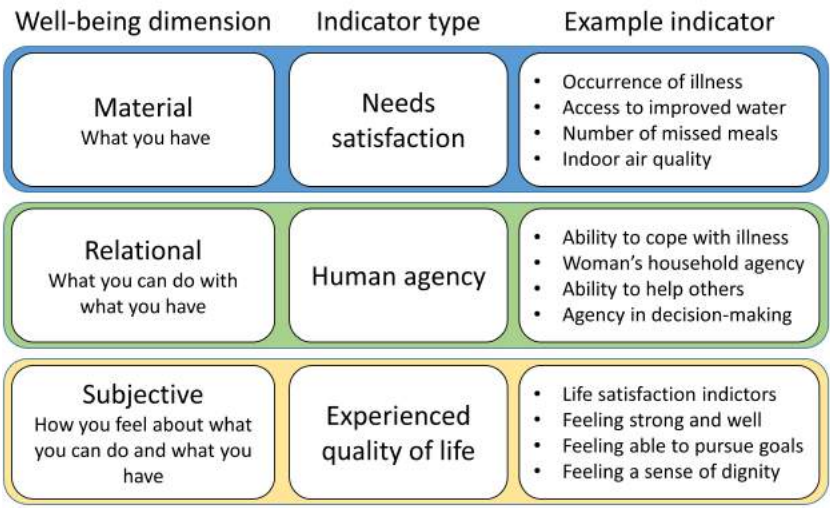

Figure 1. An example of how health can be conceptualised within well-being, adapted from McGregor and Sumner (2010), Britton and Coulthard (2013), and Woodhouse et al. (2016). Here, well-being is multi-dimensional and includes material, relational and subjective dimensions. Health relates to all three dimensions of well-being.

In this review we focus on biodiversity, rather than the environment more broadly, since it is the focus of these aligned ecological and health targets. Translating these targets into action requires understanding the connections between biodiversity and health. These connections are diverse, depend on both environmental and social factors, and our understanding of them is underpinned by evidence from a wide range of fields (Sandifer *et al.* 2015). This evidence base is rapidly growing, as illustrated in the joint CBD-WHO report *Connecting Global Priorities: Biodiversity and Human Health: A State of Knowledge Review* (CBD and WHO 2015).

Yet, there are many links in the chain between biodiversity change and human health outcomes. We argue that these are often complex and sometimes poorly understood, creating areas of uncertainty for policy-makers (Smith and Stern 2011; Jensen and Wu 2016). Failing to manage this uncertainty creates challenges for effective decision-making and risks wasting resources, creating undesired consequences, and "locking in" maladaptation (Swanson *et al.* 2010; Juhola *et al.* 2016). This uncertainty can exist as the result of lack of knowledge about a system, the inherent unpredictability of a system itself, or because of multiple interpretations of the same information (Brugnach *et al.* 2008).

Reducing the first source of uncertainty – lack of knowledge – requires understanding where knowledge gaps exist and identifying areas of uncertainty. Managing the second source of uncertainty – system unpredictability – requires incorporating risk management approaches into decision-making. Managing the final source of uncertainty – multiple interpretations of the same information – requires communication and reconciliation to narrow down to the most realistic interpretation. It may also require clarifying terminology and concepts, or alternatively using more heuristic processes to think through complex interdisciplinary challenges (Berbés-Blázquez and Feagan 2014; Seddon *et al.* 2016; Roe *et al.* 2018).

1.1 The purpose and approach of the report

The purpose of this report is to contribute to addressing this first source of uncertainty: lack of knowledge. Specifically, rather than providing a broad account of the many possible links between biodiversity and health, such as found within the joint CBD and WHO (2015) report discussed above, we seek to provide a narrow but deep examination of the causal chain linking biodiversity and health for one particular case study. This is intended to highlight some of the many unanswered questions and assumptions surrounding claimed linkages between linking biodiversity and health. Identifying these gaps may help avoid wasting resources, locking in maladaptation and creating undesired consequences. It may also offer direction on future areas of research.

A useful step in identifying areas of uncertainty is a clear conceptual framework for how biodiversity and health are linked (Tomich *et al.* 2010). A large number of conceptual frameworks exist for understanding links between natural systems and human well-being (MA 2005; Myers *et al.* 2013; Fisher *et al.* 2014; Díaz *et al.* 2015; Bayles *et al.* 2016; TEEB 2018). Here we combine a number of existing frameworks to relate changes in biodiversity to health outcomes, taking into account social processes.

With this framework, we then aim to describe some key knowledge gaps in the pathway between biodiversity and health using one example: water quality. Water quality is a useful example, since it has strong links with health and well-being, and is influenced by environmental dynamics such as upstream pollution. For instance, diarrhoeal disease alone accounted for an estimated 1.31 million deaths and 71.59 million disability-adjusted life years (DALYs) globally in 2015, with 57% of the diarrhoeal disease burden attributable to environmental factors like drinking water quality (Prüss-Ustun *et al.* 2016; GBD Diarrhoeal Diseases Collaborators 2017). However, many of the gaps identified in this example apply to other sectors in which biodiversity and health are linked, for example, the contribution of wild foods to nutritional outcomes (e.g. Rowland *et al.* 2017).

The report attempts to provide a rapid review of empirical evidence for each of the links in the causal chain outlined in the conceptual framework. This involved the purposeful selection of key literature, rather than the use of systematic review methods. As a result, this report does not attempt to provide a comprehensive assessment of the vast body of literature relating to each of the links in the causal chain.

1.2 The audience

The report is primarily targeted at technical audiences involved in developing joint biodiversity and health targets. This may include scientists, representatives from government, or those working in intergovernmental organisations.

1.3 The scope

There may be a large number of potential direct and indirect links between biodiversity and health, including through the flow of ecosystem services. Here we aim to provide a narrow but deep synthesis of evidence linking biodiversity and health using the specific example of water quality services, describing mechanisms where possible. We focus on the direct pathways linking biodiversity and health but also describe the role of biodiversity in supporting wider ecosystem processes that affect water quality.

There are many frameworks for understanding socio-ecological systems (Binder *et al.* 2013). Here we primarily utilize the ecosystem service and natural capital frameworks. These frameworks have evolved over the last decade in several ways. This includes the recognition that ecosystem services are co-produced through interacting social and ecological systems and the importance of power, justice, institutions and governance in understanding the management and distribution of services (Few 2013; Pascual and Howe 2018). This report, therefore, discusses the co-production of ecosystem services, and briefly reviews the distribution of health outcomes between groups and over time and space. The report does not, however, attempt to engage deeply in topics including power, justice and governance; the plurality of value systems; gender dimensions; the links between health and well-being; the range of ways that health can be conceptualised; or social-ecological systems theory outside the remit described above.

Water quality also has a crucial role in many other systems, such as food production, which affect health. Yet, this review does not discuss how water quality affects these other sectors. The conceptual framework presented combines existing frameworks and does not claim to develop new concepts related to socio-ecological system dynamics (described in *Appendix 1: The Conceptual Framework*). The report primarily draws on literature from the fields of ecology, environmental science, public health and environmental economics.

1.4 Overview of the report

The following section briefly introduces the conceptual framework connecting biodiversity to health (see Appendix 1). Following this, we focus on the example of water quality, situating evidence on the causal chain described in the conceptual framework. Finally, we identify a number of general policy pointers for those involved in developing joint biodiversity and health targets.

2. Conceptual Framework

A number of existing frameworks describe links between ecosystems and human well-being. Pascual and Howe (2018) draw the distinction between "core" (a fundamental part of mainstream approaches) and "satellite" (influencing the core frameworks, or drawing on them to answer specific questions) frameworks. The conceptual framework used here draws on several core and satellite frameworks, primarily those from the *Millennium Ecosystem Assessment* (MA) (MA 2005), *The Intergovernmental science-policy Platform on Biodiversity and Ecosystem Services* (IPBES) (Díaz *et al.* 2015), and articles by Jones *et al.* (2016), Myers and Patz (2009), and Myers *et al.* (2013).

The MA provides conceptual models illustrating feedbacks between direct and indirect drivers of change, ecosystem services and human well-being (MA 2005). The IPBES builds on the MA, providing a holistic approach to describe the flow of nature's benefit to people (Díaz *et al.* 2015). Jones *et al.* (2016) explicitly describe the interaction of human-derived and natural capital in co-producing ecosystem services and the importance of considering if a service meets a demand. Myers and Patz (2009) and Myers *et al.* (2013) frame the links between ecosystem services and health, and the importance of mediating factors. Here we combine these existing frameworks to help identify and interrogate assumed links between biodiversity and health.

The conceptual model describes a socio-ecological system. A socio-ecological system can be simply defined as a "system of people and nature", which has typically co-evolved over time (Thomas *et al.* 2012; Berbés-Blázquez *et al.* 2016) (see *Glossary* for a fuller definition). The framework may be applied to individuals or groups and anticipates variability between individuals and groups, and over space and time. The following introduced each of the main parts of the conceptual model, illustrated in Figure 2.

Biodiversity and ecosystem processes

Biodiversity is the "variability among living organisms [...] and the ecological complexes of which they are part" (UN 1992). Biodiversity includes species, functional and phylogenetic diversity (Biswas and Mallik 2011).[1] Generally, more biodiverse systems have more productive and stable ecosystem processes (Kotowska *et al.* 2010; Cardinale *et al.* 2012; Roscher *et al.* 2012; Gross *et al.* 2013; Latzel *et al.* 2013; Pillar *et al.* 2013; Polley *et al.* 2013; Majeková *et al.* 2014; Tilman *et al.* 2014; Oliver *et al.* 2015; Zhu *et al.* 2016).

[1] Species diversity is the number of species and their relative abundance (Hamilton 2005). Functional diversity is the range and distribution of what organisms do in ecosystems (Schleuter et al. 2010). Genetic diversity is the amount of variation in genetic information within and among individuals, species, or other ecological units (UN 1992b; UNEP-WCMC 2019).

Ecosystem processes, biological stocks and the world's capital

Ecosystem processes regulate the flux of energy, materials and information within a system (Costanza *et al.* 1997; Robinson *et al.* 2013; Jones *et al.* 2016; Mace 2019). These processes constitute the earth's biological stocks, which interact with other stocks (including atmospheric, hydrological, pedological and geological stocks) to maintain natural capital (Carpenter *et al.* 2009).

Natural capital is the world's stock of natural assets that affect humanity (Dickie *et al.* 2014) (Box 1 in Figure 2). Natural capital is one of six types of the world's capital, which also includes human, produced, social, cultural and financial capitals, which are collectively referred to as human-derived capital (Box 2 in Figure 2) (Solesbury 2003; Jones *et al.* 2016).

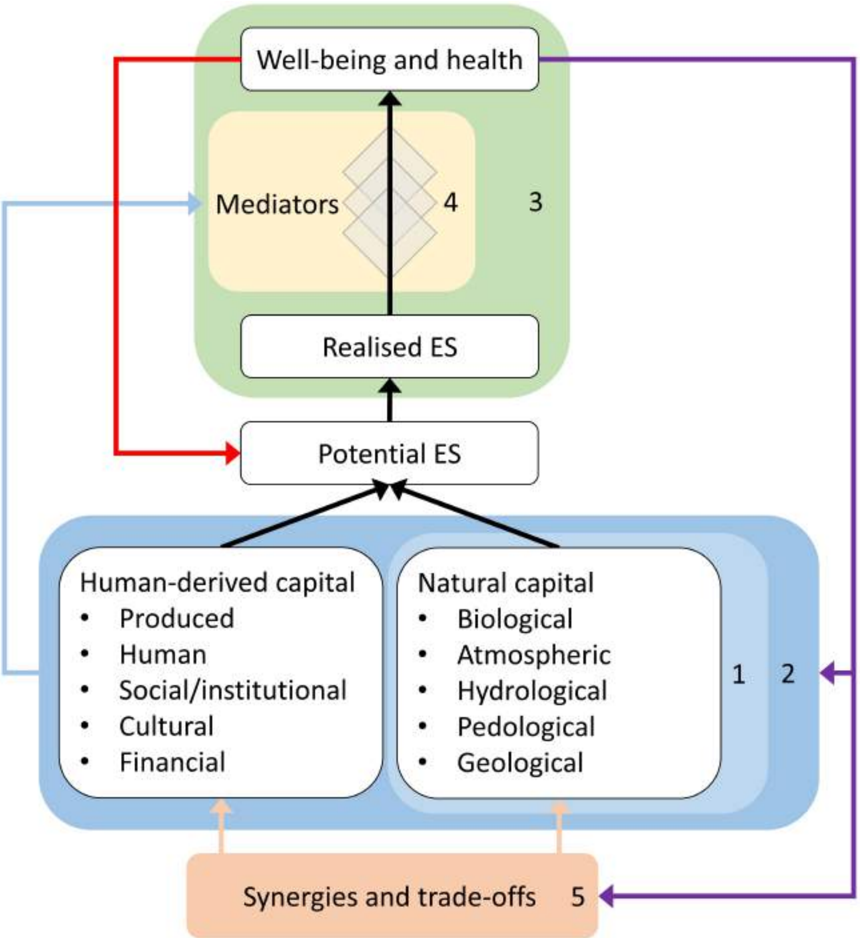

Figure 2. Biodiversity is a key component of biological stocks that interact with other stocks to maintain natural capital (Box 1). Natural capital and human-derived capital co-produce potential ecosystem services (ES) (Box 2). These services include supporting services that maintain natural capital, and provisioning, cultural and regulating services, which are collectively referred to as final services. Demand (red line) turns potential ecosystem services into realised services, and additional human capital is employed to utilise the service (blue line). These realised ecosystem services may contribute to human health and well-being (Box 3). However, mediating factors moderate the link between changes in services and human health outcomes (Box 4). Change within the system is mainly driven by reconfiguration of human-derived and natural capital, which can change the flow of services (Box 5 and brown lines). Black arrows describe the flow of potential and realised ecosystem services. The purple line describes potential feedbacks between health and the processes that drive changes in capital.

Natural capital, human-derived capital and ecosystem services

Natural and human-derived capital interact to generate *potential* ecosystem services (Jones et al. 2016).[2] Ecosystem services are natures benefit to people; they include supporting services that maintain the generation of other services, and provisioning, cultural and regulating services, which are collectively referred to as final services (MA 2003; Díaz *et al.* 2015).[3] Demand for a service is required to turn a *potential* service into a *realised* one; socio-ecological flows and processes only become services when they are demanded by users (Tallis *et al.* 2012). Furthermore, human-derived capital inputs are also often required to utilize the service (Jones et al. 2016).

Ecosystem services and health

Health is the state of physical, mental and social well-being (WHO 1946). Final ecosystem services can affect health both directly and indirectly in multiple ways (Box 3 in Figure 2) (Sandifer *et al.* 2015; Bayles *et al.* 2016). Supporting services do not themselves influence human well-being, including health, but underpin the flow of final ecosystem services (Corvalan *et al.* 2005).

Mediating factors

Intermediary processes mediate the relationship between ecosystem service flow and health in several ways (Box 4 in Figure 2). First, changes in service flows may only affect health if there is an unmet demand for that service (Myers and Patz 2009). Second, a population may be able to substitute a declining service, either with another ecosystem service or through technological and infrastructural adaptations. Finally, multiple mediating factors, such as behavioural change or institutional innovation, can insulate populations from, or expose them to, changes in a service flow (Myers *et al.* 2013). These intermediary processes can vary between groups and over scales (see *Biodiversity, ecosystems, and health over scales and between groups*).

Drivers of change in the link between capital, ecosystem services and health

Altering the composition of stocks, and their relationships with each other, may change the flow of health-related ecosystem services (Berkes *et al.* 2000; Villamagna *et al.* 2013; Price 2014) (Box 5 in Figure 2). This can include increasing the flow of one service at the expense of another, trading off the flow of a single service over time or space, increasing multiple service flows synergistically, or a combination of these (Rodríguez *et al.* 2006; Tallis *et al.* 2008; Howe *et al.* 2014).

There are also often multiple feedback processes that can dampen or intensify relationships within socio-ecological systems (Lambin and Meyfroidt 2010; Miller *et al.* 2012; Binder *et al.* 2013). These feedback processes may represent additional important drivers of change in health-related service flows.

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[2] Although biodiversity is described as a regulator of ecosystem processes, it can also be a direct source of final ecosystem services, such as the value of genetic diversity for bioprospecting or aesthetic values (Mace et al. 2012).

[3] Provisioning services are the goods derived from ecosystems, cultural services are the nonmaterial gains from nature, and regulating services are the benefits from the regulation of ecosystem processes (MA 2003). Supporting services are those processes that underpin the generation of other ecosystem services.

Biodiversity, ecosystems, and health over scales and between groups

Numerous factors can determine who “wins” and “loses” from changing ecosystem service flows, including those related to health (Takeda and Røpke 2010; Daw *et al.* 2011; McShane *et al.* 2011). Power and capacities to mobilise capital shapes governance, access and control within socio-ecological systems (Berbés-Blázquez *et al.* 2016). This can allow some groups to manage socio-ecological processes to generate private benefits whilst also creating social externalities, such as degradation of health-related service flows (Fisher *et al.* 2014). Similarly, some groups may have greater capacity and power to utilize human-derived capital to insulate themselves from changing service flows, again including those related to health (Myers et al. 2013; Fisher et al. 2014). There can also be variation in the distribution of service flows over time and space. Services are produced at different spatial scales, and this can determine at what locations health costs and benefits accrue. Similarly, service flows can change over time. Notably, there is a growing concern that current development trajectories increase the flow of final services but harm the integrity of underpinning natural capital (Raudsepp-Hearne *et al.* 2010; Shepherd *et al.* 2016). See *Appendix 1* for a more detailed description of the conceptual framework.

3. The Evidence Base – Water Quality

The previous section sought to outline briefly a conceptual framework linking biodiversity to health, drawing on ecosystem service and natural capital theory. The following section maps selected evidence onto this conceptual framework to highlight areas of uncertainty. Water quality is chosen as an example of how biodiversity and health may be linked. The continued supply of water-related services will be crucial for achieving many of the SDGs, such as those related to food security (SDG 2), health and well-being (SDG 3), energy security (SDG 7) and sustainable cities (SDG 11). The sixth Global Environment Outlook emphasises the need to manage the links between water and human health to achieve the long-term vision of a "Healthy Planet, Healthy People" (UNEP 2019).

Water quality is strongly linked to health, with diarrhoeal disease being the fourth leading cause of death among under-fives in 2015, and particularly fatal in sub-Saharan Africa and South Asia (GBD Diarrhoeal Diseases Collaborators 2017). An estimated 1.1 billion people use drinking water that suffers from moderate or worse faecal contamination, particularly in rural areas and in Africa, while 159 million people are exposed to waterborne illness through their dependence on surface water sources for drinking (WHO and UNICEF 2017).

Water quality is influenced by a wide range of environmental factors, potentially including ecological processes linked to biodiversity. Globally, water systems that support both human water security and biodiversity are heavily threatened (Vörösmarty *et al.* 2010). For example, there was an estimated average loss of 6% tree cover among the world's 230 watersheds between 2000-2014 (World Resource Institute 2016). This is partly driven by agricultural expansion, one of the largest drivers of permanent forest loss (Curtis *et al.* 2018). Many processes that threaten biodiversity within a watershed are also direct threats to health. For example, livestock grazing, which covers 26% of the world's ice-free surface, can precipitate forest clearance in some areas and can also result in oral-faecal transmission of several diarrhoea-causing pathogens, such as zoonotic cryptosporidium (Hunter and Thompson 2005; Steinfeld *et al.* 2006; Kotloff *et al.* 2013; McDaniel *et al.* 2014)

We expect biodiversity to play a role in enhancing water quality, in the face of these threats, in turn supporting human health. Yet, these causal connections rely on multiple assumptions. We seek to provide evidence of each of the links in the causal chain between biodiversity and health, through water quality. Each section ends with a summary (blue boxes). Additional insets (green boxes) discuss specific themes.

3.1 Biodiversity, water quality and human health

This section briefly outlines the potential causal pathway that links biodiversity to health within a hypothetical watershed example (Figure 3). This hypothetical watershed is a socio-ecological system. Following our conceptual framework, we situate biodiversity as a core part of biological stocks, nested within natural capital. Water quality is a provisioning ecosystem service co-produced through the interaction of stocks, nested in human-derived and natural capital. The amount of water quality services utilised depends on the demand for water for drinking and other activities. Surface water quality may affect health (see Table 1 for examples). However, the effect of a change in water quality on health is mediated by factors such as household's water source or water treatment behaviour. Drivers of change within this hypothetical watershed include agricultural expansion, associated with reduced water quality. There are also feedback processes, such as where those that are ill harvest timber to pay for healthcare.

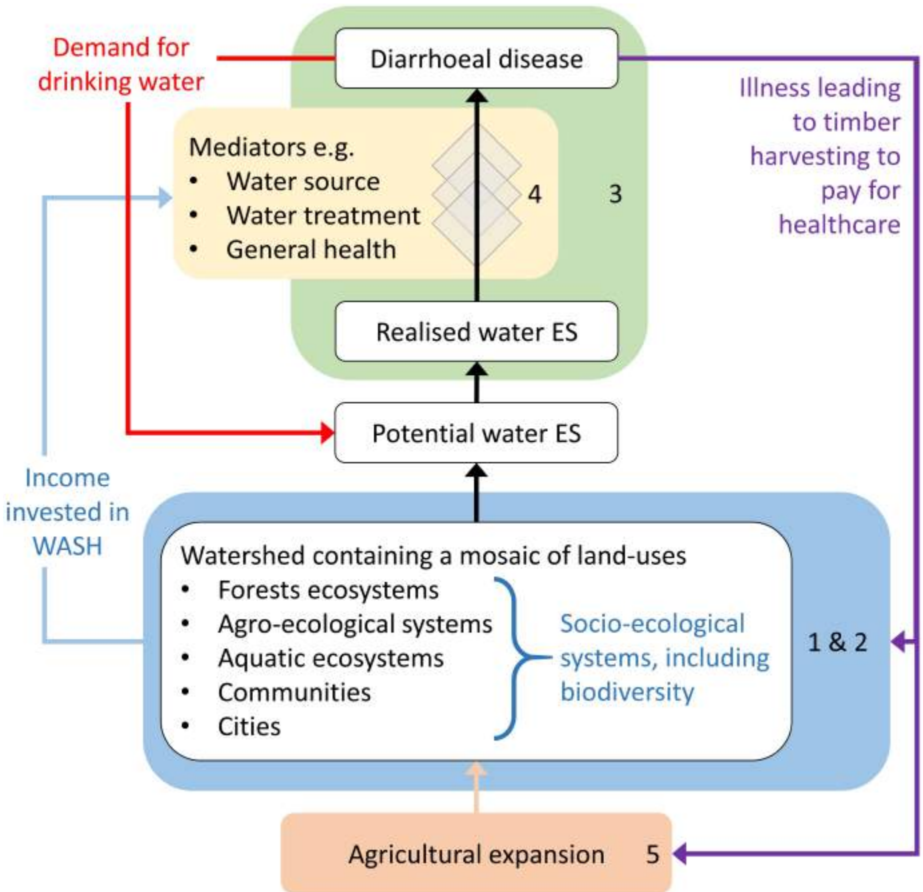

Figure 3. A stylised example of how biodiversity might be linked to diarrhoeal disease within a watershed, using the framework described in Figure 2. Biodiversity is a core part of biological stocks. Stocks nested within human-derived and natural capital are reflected in a mosaic of land uses and human activities (Boxes 1 and 2). Surface water quality is a provisioning ecosystem service co-produced by human and natural capitals within the watershed. The amount of the service utilized depends on the demand for drinking water (red line). Surface water quality may be linked to the risk of diarrhoeal disease (Box 3). However, the effect of a change in water quality on health is mediated by multiple factors (Box 4). Human-derived capital can be invested in enhancing these mediating factors, such as through improved water, sanitation and hygiene (WASH; blue line). The major driver of change within this hypothetical system is agricultural expansion, which is associated with reduced water quality (Box 5). There is also an example feedback process, where illness leads to timber harvesting to generate income for healthcare, thereby facilitating increased agricultural expansion and also reducing stocks of natural capital, including biodiversity (purple lines).

Table 1. Examples of how biodiversity may be linked to water quality, and how water quality could affect different health outcomes, mediated by factors associated with human-derived capital.

Biodiversity	Water quality	Example moderators	Example health outcome
Increased productivity elevating microbial activity	Pathogenic deactivation through lysis	Social capital enabling access to improved water sources	Diarrhoeal disease (physical and mental health)
Niche complementarity elevating biomass production	Physical filtration of macro-nutrients	Power to prevent others from engaging in polluting activity	Thyroid cancer (physical health)
Community stability supporting specific species	Micro-pollutant remediation from functional traits	Financial capital to move to a less polluted area	Endocrine disruption (physical health)
Niche complementarity increasing community resource use	Uptake of macro-nutrients	Access to water bodies for recreation	Depression and social relations (mental and social health)

Economic valuation of water quality services

There is a long history of valuing water quality services in economic terms, such as a study in the late 1980s looking at the economic value of drinking water from lakes (d'Arge and Shogren 1989). Multiple reviews present evidence of the economic values of water quality services. For instance, the mean value of wetland regulating services in agricultural landscapes across 27 estimates was US$5,788 per hectare per year (Brander *et al.* 2013).

Using value-transfer approaches, the total global value of wetland regulating services in agricultural landscapes were estimated to be over US$26 billion per year (although the authors recognise the high uncertainty of this estimate). An earlier meta-analysis estimated the value of water quality regulation from wetlands was over US$1,030 per hectare per year (1990 values equivalent to around US$1,630 in 2007) (Woodward and Wui 2001).

Services derived from wetland ecosystems can be among the highest valued compared to those from other ecosystems (Russi *et al.* 2013). For instance, monetary values associated with regulating services derived from inland wetlands ranged from US$321 to US$23,018 per hectare per year (2007 values adjusted for purchasing power parity) (Russi *et al.* 2013). Similarly, regulating services from rivers and lakes ranges between US$305 and US$4,978 per hectare per year. These high values reflect the multiple co-benefits derived from water quality services. Although our paper focuses on health, many watershed interventions that may be aimed primarily at improving health are likely to prove cost-effective regardless of the health benefits, when accounting for co-benefits of the type estimated in these economic analyses.

3.2 Biodiversity and water quality – Boxes 1 and 2 of Figure 3

Here we focus on the links between biodiversity and water quality. Biodiversity is only one stock within the complex configuration of stocks underpinning human-derived and natural capital found within watersheds, which interact to generate water quality services. However, we limit the discussion to the role of biodiversity for brevity.

The quality of water is defined by multiple characteristics, such as nutrient levels, the presence of pathogens and other pollutants (Smith et al. 2013). Water quality can be affected by both point and non-point sources of pollution, as well as the remediating effect of natural processes. Biodiversity may affect these characteristics and processes. Here we provide evidence for the links between species, functional and genetic diversity and the remediation of macro- (nitrogen, phosphorous, and others) and micro- (natural trace and synthetic) pollutants, and pathogen contamination. However, it is important to note that although functional diversity may be a more powerful predictor of ecosystem service flows, most studies focus on the links between species diversity and water quality (Harrison et al. 2014; Gagic et al. 2015).

Biodiversity appears to contribute to the sequestration of macro- and micro-pollutants through several mechanisms (Smith 2003). Niche complementarity occurs where a community of complementary species fill differentiated niches (Tilman et al. 1997). Niche complementarity is greater in communities with higher species, functional and genetic diversity (Fornara and Tilman 2008; Kotowska et al. 2010; Cardinale et al. 2012; Roscher et al. 2012; Latzel et al. 2013; Forrester and Bauhus 2016; Zhu et al. 2016). This complementarity may remediate macro- and micro-pollutants in at least two ways. First, niche complementarity increases the efficiency of resource capture within ecosystems, thereby reducing nutrient loads through uptake (Spehn et al. 2005; Cardinale et al. 2006; Cardinale 2011). Second, more efficient systems are also more productive (Fornara and Tilman 2008; Kotowska et al. 2010; Cardinale et al. 2012; Roscher et al. 2012; Latzel et al. 2013; Forrester and Bauhus 2016; Zhu et al. 2016; Duffy et al. 2017). Higher productivity is associated with increased biomass, which physically filters out particulate pollutants from water sources (Engelhardt and Ritchie 2001; Cardinale et al. 2006). Much of the evidence of these links are from short-term and local or lab-based studies; the long-term fate of pollutants, including if they re-enter water systems in the future, is uncertain (Balvanera et al. 2014).

Individual species may also have specific functional traits that influence water quality. Some species can biodegrade toxic micro-pollutants; more diverse systems may be more likely to contain species with these functions (Anwar et al. 2009; Rayu et al. 2012; Kaczorek et al. 2013; Rodgers-Vieira et al. 2015; Dzionek et al. 2016).

Biodiversity may also be associated with higher rates of pathogenic deactivation, with human pathogens surviving for a shorter time in more microbially active environments (Burkhardt et al. 2000; Brookes et al. 2004; van Elsas et al. 2012; Feichtmayer et al. 2017). This may be the result of microbial interactions, such as predation, lysis of bacteria, or the release of antimicrobial substances (Dashiff et al. 2011; Feichtmayer et al. 2017). These interactions may occur at a greater rate in more biodiverse environments since they are more productive (as the result of niche complementarity). Nevertheless, the fate of pathogens is largely determined by abiotic factors such as UV exposure. Additionally, biodiversity changes can affect disease ecology, such as through the dilution and amplification effects (e.g. Keesing et al. 2006; Suzán et al. 2009; Searle et al. 2011; Henderson et al. 2012; van Elsas et al. 2012). However, it appears there is little evidence describing disease ecology in the context of water quality.

Ecosystem processes, strongly determined by biodiversity, also drive wider ecological and biophysical processes that may improve water quality. For example, these processes can improve soil structure, enhancing the removal of pollutants as water passes through the soil profile (Wall et al. 2015). Biodiversity also increases ecosystem stability (discussed in Biodiversity and ecosystem processes). Some ecosystems as a whole can enhance water quality. For example, wetlands can improve water quality through a range of biochemical and physical processes (Fisher and Acreman 2004; Saeed and Sun 2012).

Potential and realised water quality services – Red line of Figure 3

Referring back to the conceptual framework, it is necessary to differentiate between *potential* and *realised* water quality service flows (Keeler *et al.* 2012). This involves identifying both the flow of potential services generated through social, ecological and hydrological processes and the beneficiaries. However, a review of 381 hydrologic services studies found that only 19% of them integrated both ecosystem service flows and beneficiaries (Brauman 2015).

A diverse system is more likely to contain species or groups that persist during disturbance, and more rapidly recover after perturbations, than a simpler one (Tilman and Downing 1994). A large body of evidence suggests that species, functional and genetic diversity stabilises ecosystems, increasing their resilience to disruption and rate of recovery (Tilman and Downing 1994; Girvan *et al.* 2005; Jiang and Pu 2009; Hector *et al.* 2010; Keith *et al.* 2010; Kotowska *et al.* 2010; Campbell *et al.* 2011; Pillar *et al.* 2013; Polley *et al.* 2013; Gross *et al.* 2013; Latzel *et al.* 2013; Loreau and de Mazancourt 2013; Majeková *et al.* 2014; Mumme *et al.* 2015; Oliver *et al.* 2015; Venail *et al.* 2015; Wang and Loreau 2016). Less variable ecosystems are expected to provide a more stable flow of services than more variables ones (Schindler *et al.* 2010; Balvanera *et al.* 2014; Oliver *et al.* 2015; Isbell *et al.* 2017). For example, one study finds that the flow of water quality services in England and Wales fluctuated over time, although the causes of variation were unclear (Holland *et al.* 2011).

Nevertheless, it is worth recognising that biodiversity is one of the multiple factors determining water quality within a watershed catchment (e.g. Naiman and Decamps 1997). Many catchments are mosaics of different landscape features, representing configurations of stocks nested within natural and human-derived capital, which can interact to affect water quality (Allan 2004). A recent review found that among the 780 papers exploring links between natural capital factors and ecosystem services, 171 found positive or negative effects on water quality regulation (Smith *et al.* 2017). By far the largest studied group of factors related to habitat and vegetative cover, with 64% of the 171 studies finding a positive relationship. Comparatively, 7% of studies described positive relationships between biodiversity and water quality regulation, but 23% found a positive relationship with a specific species or functional group (Smith *et al.* 2017). However, as noted by the authors of the review, there is ample evidence that biodiversity is necessary for supporting ecosystems over time. As such, the beneficial role of biodiversity may have been obscured in studies that simply looked at vegetative cover. As a result, we argue it remains unclear what fraction of water quality services could be attributed to the role of species, functional and genetic diversity. Furthermore, at a watershed level, the extent to which water quality is determined by ecological processes or simply the absence of sources of contamination is contestable.

Section summary – Biodiversity and water quality (Boxes 1 and 2 of Figure 3)
Overall, there is evidence that species, functional and genetic diversity enhances water quality, and may stabilize water quality services over time. However, the significance of biodiversity compared to other stocks within natural and human-derived capital remains unclear.

3.3 Water quality and human health – Box 3 of Figure 3

Here we emphasise the distinction between biodiversity and other ecological and biophysical factors, specifically seeking to provide mechanistic explanations linking biodiversity and health. The following focuses on the role of waterborne pathogens and macro- and micro-pollutants in human health, as a key aspect of water quality. We discuss some of the indirect and direct effects of these contaminants, and the limited evidence explicitly linking health outcomes to biodiversity via water quality. This evidence includes physical, social and mental health aspects, reflecting the WHO definition of health (WHO 1946).

Although the majority of the world's population benefits from improved drinking water sources, there is strong regional heterogeneity. For instance, 42% of sub-Saharan Africans do not have access to basic drinking water services (WHO and UNICEF 2017). Diarrhoeal disease as a consequence of inadequate drinking water was estimated to have caused over 500,000 deaths and nearly 34 million DALYs globally in 2012 (Prüss-Ustün *et al.* 2014).

Most of the variation in diarrhoeal disease (57%) is attributable to environmental factors, including the built, social and natural environment (Prüss-Ustun *et al.* 2016). In particular, the burden of diarrhoeal disease attributable to environmental factors may be particularly high in landscapes dominated by livestock farming, where cryptosporidium is shed in livestock faeces, but residents are dependent on surface and improved drinking water sources. High livestock densities and low levels of improved water sources appear to coincide in sub-Saharan Africa on the fringes of the Congo Basin (Robinson *et al.* 2014; WHO and UNICEF 2017). African countries also have some of the highest rates of diarrhoeal disease in the world. In these and other areas, diarrhoeal disease risk may be sensitive to changes in water quality services.

Replacement costs of water quality ecosystem services

Replacement costs are a useful way of estimating some of the water quality regulation values attached to ecosystems. One study estimated that ecosystem degradation within catchments increased the cost of water treatment in 29% of cities globally (McDonald *et al.* 2016). Within affected cities, the average operation and maintenance costs increased by over 50% and replacement capital costs increased by nearly 45%. This represented a net present cost to municipal utilities of US$5.4 billion annually (McDonald *et al.* 2016). Other studies also use replacement cost methods to estimate the economic value of ecosystems for water quality. For instance, one study in South Africa estimated that the value of Fynbos biome wetlands in removing ammonium nitrogen from water was US$1,913 per hectare per year (Turpie *et al.* 2010).

Many of these studies do not calculate opportunity costs for land, and so do not capture the net value of water regulation services. However, often the value of ecosystem services can exceed the value of alternative land uses (de Groot *et al.* 2012). For example, one study assessed the value of restoring forested wetlands through the Wetlands Reserve Program in the Mississippi Alluvial Valley in the United States (Jenkins *et al.* 2010). The study assessed a range of services including nitrogen mitigation, which had an estimated value of US$1,248 per hectare per year. They find that the potential value for associated ecosystems services can exceed the opportunity cost for landowners, suggesting that market-based payments could incentivise landowners to protect watersheds.

Water quality and pathogens

As discussed, pathogens tend to deactivate more rapidly in microbially active environments as a result of antagonistic interactions (Dashiff *et al.* 2011; Feichtmayer *et al.* 2017). However, these biological factors are likely to play relatively modest roles in determining the fate of pathogens, since their fate is predominantly determined by abiotic factors. Additionally, there appear to be non-linear dose-response relationships between pathogenic contamination of water and diarrhoeal disease, indicating diminishing marginal returns to improved water quality (Keeler *et al.* 2012; Gruber *et al.* 2014). More generally, there appears to be no evidence identifying declines in biodiversity as a risk factor for waterborne diseases in people. As a result, it is unclear what portion of waterborne disease could be mitigated through the management of biodiversity specifically.

Biodiversity and habitat cover often co-vary, and so looking at associations between land use and health outcomes may provide some indication of the role of biodiversity in health. A number of studies look at the association between land cover and health outcomes. It is estimated that 30% greater upstream tree cover was associated with 4% lower probability of diarrhoeal disease, similar to that of households utilizing improved sanitation facilities, among rural children in 35 countries (Herrera *et al.* 2017). Similarly, 10-percentage point lower tree cover was associated with 14.1% greater incidence of diarrhoea in children in 19,231 households in Cambodia (Pienkowski *et al.* 2017). Higher base water flows were associated with lower diarrhoeal disease around a protected forest in Indonesia (Pattanayak and Wendland 2007). Moreover, those living near strictly protected areas in the Brazilian Amazon had a significantly lower incidence of diarrhoea than those that did not

(Bauch *et al.* 2015). One study found that forest loss was associated with lower diarrhoeal disease in Niger (Berazneva and Byker 2017). However, this study did not include important potential confounders, and so their estimates may be unreliable. These studies are purely correlative, and further evidence is needed before causal relationships can be established. Although the role of biodiversity in these results is unclear, it does appear that more intact landscapes are associated with lower diarrhoeal incidence among those dependent on surface water.

Water quality and macro- and micro-pollutants

Pathogens are not the only source of water contamination that might affect health. Macro-pollutant contaminants within water can, directly and indirectly, damage health in multiple ways. As an example of direct effects, nitrite contamination appears to increase the risk of some forms of cancer such as thyroid cancer (Ward 2009; Ward *et al.* 2010). Nitrite may increase the risk of reproductive problems, "blue-baby syndrome" and other adverse health outcomes (Townsend et al. 2003). As an example of indirect effects, nutrient run-off can lead to lead to toxic algal blooms, create aquatic dead zones that affect fisheries and subsequently human nutrition, or alter disease ecology (Anderson *et al.* 2002; Johnson *et al.* 2010; Erisman *et al.* 2013).

Micro-pollutants include thousands of natural and synthetic trace contaminants. Even at low concentrations, these micro-pollutants can have detrimental effects, which are often challenging to detect because they can have cumulative and interacting effects (Schwarzenbach *et al.* 2006). Moreover, these pollutants can interact with the biotic and abiotic environment to change their toxicity in unknown ways. As a result, these micro-pollutants – including trace metals and persistent organic pollutants (POPs) – can have diverse but unclear effects on health.

Around 30 naturally occurring metals and metalloids may be harmful to human health and can enter the environmental naturally or through human disturbance (Morais *et al.* 2012). Some of the most commonly found metals in water sources are arsenic, cadmium, chromium, copper, lead, nickel and zinc (Jaishankar *et al.* 2014). For example, lead affects many functions in the human body and can have harmful reproductive, respiratory, neurological and developmental effects (Wani *et al.* 2015). Similarly, cadmium can cause kidney damage, harm reproductive health, may cause bone damage and increase the risk of some cancers as well as having acute toxic effects (Godt *et al.* 2006).

POPs persist in the environment, can be transported over large distances, tend to bioaccumulate through food webs and are toxic (Schwarzenbach *et al.* 2010). POPs may increase the risk of some cancers, cardiovascular disease, diabetes, obesity, and cause reproductive and behavioural problems (Qing Li *et al.* 2006; Schwarzenbach *et al.* 2010; Alharbi *et al.* 2018). Some POPs are endocrine disrupters, which include a wide range of synthetic organic chemicals (pharmaceuticals, pesticides like DDT, plastic components including bisphenol A and dioxin-like compounds) that disrupt endocrine systems (Schug *et al.* 2012).

As discussed in *Biodiversity and water quality – Boxes 1 and 2 of Figure 3*, biodiversity may contribute to both macro- and micro-pollution (including metals and POPs) remediation, thereby improving the health of exposed populations. This may occur directly, where functionally diverse systems contain organisms that can bioremediate or physically filter out pollutants (Spehn *et al.* 2005; Cardinale *et al.* 2006; Cardinale 2011; Kaczorek *et al.* 2013; Rodgers-Vieira *et al.* 2015; Dzionek *et al.* 2016). It may also occur indirectly, where the supporting services provided by biodiversity maintains ecosystems. However, as in the case of pathogens, there appears to be no evidence that that directly evaluates the role of biodiversity in reducing illness associated with macro- and micro-pollution.

Water quality and social and mental health

The effects of water quality are not limited to physical illness. Within Bangladesh, higher levels of arsenic contamination of water were associated with worse mental health (Edmunds *et al.* 2015; Chowdhury *et al.* 2016). Qualitative evidence suggested that concern over water quality was a stressor that may increase the risk of mental illness in Flint, Michigan (Cuthbertson *et al.* 2016). Additionally, mental illness is frequently co-morbid with physical illnesses (Prince *et al.* 2007). For instance, there appear to be bi-directional relationships between irritable bowel syndrome and depression and anxiety disorders (Whitehead *et al.* 2002; Shah *et al.* 2014). Relatedly, there is evidence that childhood diarrhoeal illness can cause cognitive impairment later in life (Pinkerton *et al.* 2016). Consequently, the role of biodiversity in regulating water quality may have both direct and indirect impacts on mental health through physiological illness. Yet, sparse evidence explores these potential links empirically, particularly the remediating role of biodiversity.

Another important but often neglected aspect of health is social health. Social health can be defined as the factors that influence a person's well-being related to their relationships with others, including how they interact with society and social institutions in general (McDowell 2006). Social health is sometimes discussed in the context of people's ability to maintain social lives whilst managing physical and mental illness (e.g. Huber *et al.* 2011). However, when looking at the WHO definition of health, social health is seen as an objective in its own right, since social relations strongly contribute to well-being (WHO 1946; McDowell 2006). Social health, rather than social determinants of health, appears to get relatively little attention compared to physical and mental aspects. Yet, links between social health and water quality are recognised. As the late United Nations Secretary-General Kofi Annan stated: "Contaminated water jeopardizes both the physical and social health of all people" (WHO 2003). Nevertheless, there appears to be little research directly exploring the links between social health and biodiversity (or any other element of natural capital) in the context of water quality.

Section summary – Water quality and human health (Box 3 of Figure 3)
In summary, there is evidence of mechanisms by which biodiversity could affect health through water quality services. However, there appear to be no empirical estimates of the magnitude of the health impact resulting from changes in biodiversity (the attributable fraction). There is some evidence that more ecologically intact landscapes may be associated with a lower risk of diarrhoeal disease, a major cause of morbidity among children in low and middle-income countries. There appears to be limited research looking at the effect of intact ecosystems on health outcomes related to other aspects of water quality. Furthermore, much of the research on water quality has focused on physical health, neglecting mental and social aspects.

3.4 Mediating factors between water quality and human health – Box 4 of Figure 3

Globally, although diarrhoeal disease remains an important health challenge, the number of deaths due to diarrhoea has declined by an estimated 20.8% between 2005 and 2015 (Troeger *et al.* 2017; IHME 2018). These gains are partly attributed to improvements in water quality, sanitation and hygiene. For instance, the Millennium Development Goal target for drinking water was surpassed with 91% of the world's population using improved drinking water sources by 2015 (WHO 2015). At an individual level, people may also alter their behaviour as a result of changes in perceived water quality. For example, experimental studies in rural India showed that information about water contamination changed water use behaviour, with people shifting towards safer commercial water sources (Hamoudi *et al.* 2012). These adaptations represent a process of behavioural, technological and institutional change decoupling health from ambient water quality. However, although human-derived capital can be mobilised to buffer against watershed degradation, often with technical substitutes, the associated gross costs can be substantial (see inset *Replacement costs of water quality ecosystem services*) (Turpie *et al.* 2010; McDonald *et al.* 2016).

Although there is overwhelming evidence that basic improvements in drinking water, sanitation and other measures can improve health, there appears to be limited evidence of how these mediate the links between biodiversity and health. Although not focused on biodiversity, the study conducted by Herrera *et al.* (2017) found that the positive effect of tree cover on diarrhoea incidence was higher among those that did not treat their drinking water, indicating that treatment insulates people from changing ecosystem service flows. We found no studies estimating the role of mediating factors on the pathway between biodiversity and health through water quality.

Section summary – Mediating factors between water quality and human health (Box 4 of Figure 3)

There appears to be limited evidence of how mediating factors dampen or exacerbate health impacts specifically attributed to biodiversity change. However, there is rich evidence describing the range of behavioural, technological and institutional innovations that exist to insulate people from poor water quality. As a result, the effect of biological change on health, through water quality, is likely to be strongly influenced by mediating factors.

Climate change, water quality services and health

Climate and biodiversity change may increasingly interact to affect health in the future. A substantial body of evidence explores the ways that climate change could increase the risk of waterborne disease through multiple mechanisms (Levy *et al.* 2016). Heavy rainfall and flooding often increase the risk of diarrhoea, even in countries where diarrhoeal morbidity is low. For example, multi-year studies in the US, UK, Ecuador, Mozambique, Ethiopia and other countries suggest that heavy rainfall was positively correlated with increased diarrhoeal incidence (Rose *et al.* 2000; Curriero *et al.* 2001; Nichols *et al.* 2009; Carlton *et al.* 2014; Azage *et al.* 2017; Horn *et al.* 2018). This may occur if heavy rainfall mobilises and transports pathogens into surface and groundwater sources or compromises municipal water systems (Levy *et al.* 2016). It appears that vegetative cover can reduce peak flows and flooding, although this effect is not universal (Robinson *et al.* 2003; Brown *et al.* 2005; Filoso *et al.* 2017; Guzha *et al.* 2018). As a result, those living in more ecologically intact watersheds, including areas with currently low diarrhoeal incidence, could be better insulated from the effects of climate change on waterborne illness.

3.5 Drivers of change in the link between capital, ecosystem services and health – Box 5 of Figure 3

Here we do not focus on the large amount of literature describing drivers of ecosystem service change. Instead, we focus on evidence of how those changes may create health trade-offs. Since little evidence focuses specifically on biodiversity, we discuss habitat cover as a proxy for biodiversity.

Changing the composition of stocks and subsequent ecosystem service flows may alter the risk of a range of health conditions simultaneously, increasing some whilst reducing others. It is therefore important to look at net health and clarify the trade-offs between multiple health impacts. One of the most apparent health trade-offs often exists between upstream agricultural production and downstream water quality (Verhoeven *et al.* 2006; Gordon *et al.* 2010). For example, upstream agricultural production may increase incomes that can be used to improve diets, and subsequently health (Pandey *et al.* 2016). However, this gain may be offset by greater downstream diarrhoeal disease (Herrera *et al.* 2017).

There can also be less apparent health trade-offs as the result of changing configurations of stocks. For instance, wetlands are drained to remove mosquito-breeding sites as a malaria control method (Ramirez *et al.* 2009). However, since wetlands help regulate water quality, their removal might increase the incidence of other types of illness in downstream communities (Fisher and Acreman 2004; Saeed and Sun 2012).

Although these trade-offs are important for understanding the net health effects of environmental change (which can include biodiversity change), a limited number of studies look at illness associated with water quality and other health outcomes simultaneously. Bauch *et al.* (2015) find that living in proximity to strictly protected areas in the Brazilian Amazon was associated with a lower incidence of malaria, acute respiratory infection (ARI), as well as diarrhoea. Similarly, Pienkowski *et al.* (2017) find similar relationships between fever and ARI and proximity to protected areas in Cambodia. Additionally, they find that forest loss was associated with higher rates of ARI, fever and diarrhoea. Again, the results of these studies do not establish causation and so should be treated with caution. Furthermore, they do not look at the health trade-offs associated with changes in biodiversity specifically.

Section summary – Drivers of change in the link between capital, ecosystem services and health (Box 5 of Figure 3)
There is some evidence describing how multiple health outcomes simultaneously respond to land-use change, but not biodiversity. Furthermore, it appears like there have been no attempts so far to compare these in standardised terms, such as through the use of DALYS.

3.6 Water quality services and health over scales and between groups

The following section explores evidence of how the health costs and benefits of changes in water quality services are distributed between groups, and over spatial and temporal scales. We do not exclusively discuss evidence of the role of biodiversity. Instead, we provide evidence of the distribution of water quality-related health impacts resulting from a range of changes in stocks associated with human-derived and natural capital.

Distribution between groups

We expect groups to vary in their capacity to govern and manage socio-ecological processes, capture benefits and avoid costs associated with water quality services (Takeda and Røpke 2010; Daw *et al.* 2011; McShane *et al.* 2011; Berbés-Blázquez *et al.* 2016). For example, power asymmetries have meant that some middle-class residents of Delhi, India, are able to access improved water sources, whereas those living in low-income settlements have not (Karpouzoglou and Zimmer 2016). Such differences may have contributed to higher rates of gastric illness among poorer households in India (Szabo *et al.* 2016). The manifestation of these power asymmetries on health may be particularly pronounced in areas of rapid change, such as peri-urban landscapes, where protective institutions and infrastructure are yet to emerge or are contested (Mehta and Karpouzoglou 2015).

In particular, we expect some groups to have a disproportionate role in driving and benefiting from socio-ecological alterations associated with changes in water quality services (Fisher *et al.* 2014). If these activities cause negative health externalities, then the benefits of these activities are expected to accrue privately and to more powerful actors with the costs being borne publicly by less powerful groups. Nevertheless, there appears to be little empirical evidence of how different groups drive changes in biodiversity, water quality, and subsequently incur different health impacts.

Additionally, we expect some groups are able to insulate themselves from changing water quality, by investing in improved water sources for instance (Marmot 2005; Myers and Patz 2009; Myers *et al.* 2013). Again, we find no evidence of how groups insulate themselves from changes in water quality associated with changes in biodiversity. However, there is some evidence that improved drinking water insulates people from the potentially negative effects of land-use change on health (Herrera *et al.* 2017).

Distribution over spatial scales

Much of the evidence linking biodiversity directly to water quality comes from small-scale and lab-based studies, but the mechanisms underlying the role of biodiversity in regulating water quality at a catchment level remain unclear (Balvanera *et al.* 2014). Some studies report positive relationships between species diversity and water quality at landscape levels, whereas others report inconclusive or negative relationships (e.g., Bai *et al.* 2011; Pan *et al.* 2012). This may be unsurprising since most studies appear to focus on species diversity, whereas ecosystem services are more dependent on functional diversity, which is more challenging to measure (Cadotte *et al.* 2011). Additionally, links between biodiversity and ecosystem processes appear to weaken at larger scales; at a global level, most of the variation in primary productivity is explained by climate, resource availability and disturbance, rather than biodiversity (Dĩaz *et al.* 2005; Biswas and Mallik 2011).

There are around 205 transboundary basins greater than 10,000 km^2, intersecting with 140 countries and covering around half of the world's ice-free land area, which contained 58% of the world's population in 2010 (Munia *et al.* 2016). Consequently, water quality issues are highly transboundary. The evidence linking land use to health outcomes largely focuses on local geographical scales (e.g. Pattanayak and Wendland 2007; Herrera *et al.* 2017; Pienkowski *et al.* 2017). This spatial scale may be most appropriate for looking at associations between health outcomes and land use. For instance, across 40 Canadian catchments, changes in land use were only associated with changes in *Escherichia coli* indicators at a 5–10 km spatial scale (Hurley and Mazumder 2013). This localised association may be because of the rapid deactivation of pathogens within the environment (Dashiff *et al.* 2011; Feichtmayer *et al.* 2017). Consequently, interventions to improve water quality by reducing pathogenic loads may benefit exposed populations that are geographically close, but with limited benefits further downstream. Nevertheless, humanity's footprint extends over large areas, and so there are likely to be a significant number of people affected by these local processes.

POPs and other pollutants can persist in the environment for long periods of time, and so can be transported over large areas (Schwarzenbach *et al.* 2010). The "epidemiological transition" occurs as a population's disease burden shifts from communicable to non-communicable diseases (NCDs). As countries undergo this transition, pollutants may be an increasingly important contributor to NCDs. It may, therefore, be valuable to understand how ecosystem processes (linked to biodiversity) contributes to the remediation of these pollutants (Frumkin and Haines 2019). Yet, it may be challenging to attribute this remediation to ecosystem processes that may be geographically dislocated from pollution sources. More generally, the extent to which changes in the composition of stocks may affect health over geographical scales will vary depending on the process and health outcome in question.

Distribution over time

There are concerns that activities that threaten biodiversity can generate short-term benefits but also long-term costs, resulting in intergenerational inequity (MA 2005; Raudsepp-Hearne *et al.* 2010; Shepherd *et al.* 2016). Wetlands and other habitats and their constituent biodiversity have been recognised as important natural assets that can help regulate water quality (Brauman *et al.* 2007; Barbier 2011). Freshwater systems are some of the most threatened habitats, suggesting that associated water quality services may be particularly sensitive to exploitation (Dudgeon *et al.* 2006). However, we find little empirical evidence explicitly estimating how biodiversity loss may alter the risk of illness related to water quality in the future.

We could also conjecture that income derived from activities that threaten biodiversity may be invested in measures that improve long-term public health. The evidence above suggests that improvements in water, sanitation and hygiene can be an effective and efficient means of improving health. Consequently, watershed degradation may in some cases lead over time to net declines in waterborne disease through mediating factors related to human capital. However, this claim makes a number of key assumptions about the substitutability of water quality regulating services, the investment of income derived from natural resource exploitation into public health, and lags between resource exploitation and public health investment. These assumptions are largely untested, and there is little evidence supporting or refuting this conjecture.

Section summary – Water quality services and health over scales and between groups

There is little evidence describing how the health costs and benefits from water quality change associated with biodiveristy vary between groups. There is evidence that biodiversity may play a role in water quality at local scales, but not at larger scales. Land-use change (which can co-vary with biodiveristy) may increase the risk of pathogenic diarrhoea in nearby populations, but may have less effect downstream. Persistent and easily transported pollutants may have more far reaching health effects, but the ammelorating role of biodiveristy at these scales is unclear. There appears to be no evidence on how biodiversity change may affect health through water quality services in the future.

Overall summary – Biodiversity, water quality and human health

There are theorised mechanisms, strongly supported by evidence, by which biodiversity directly improves water quality. However, there appear to be no estimates of the effect of biodiversity on health, through changes in water quality. Nonetheless, biodiversity supports the functioning of ecosystems, and there is evidence that intact ecosystems are associated with better water quality. The economic value of these water quality services can be high. The cost of replacing those services with technical substitutes can also be high, even when taking into account the opportunity cost of watershed retention. Although humanity has been successful in reducing the rates of waterborne disease, through water, sanitation, hygiene and other measures, physical morbidity associated with poor water quality remains high in some parts of the world.

There is less evidence of the links between water quality and mental and social health, which could be important. The negative health effects of changes in ecosystem services may accrue publicly and to the most exposed populations, with the benefits accruing privately. Although pathogenic health effects may accrue at limited distances from land-use change events, a significant number of people may still be affected as a result of widespread watershed degradation. Furthermore, some pollutants can persist and be transported over large areas. Ecosystem processes (associated with biodiversity) may have an increasingly important role in remediating pollutants that contribute to NCDs as countries undergo the "epidemiological transition".

This summary suggests that there are some links between biodiversity and human health that are more certain than others. Policies to manage landscapes for health should recognise this uncertainty, whilst acting in areas of greater certainty. For example, there is reasonable evidence that protecting forested watersheds may be a cost-effective way of managing waterborne disease in populations that are dependent on untreated surface water. This need is likely to diminish as sanitation and hygiene are improved. However, maintaining intact landscapes may still be an efficient way of reducing water treatment costs, with substantial co-benefits.

4. Policy Pointers

The post-2020 global biodiversity framework is currently in development and will aim to harmonise global nature conservation efforts with the SDGs and other global accords (IUCN 2018). This includes replacing the Aichi targets with a new generation of objectives. Health is likely to be an important component of the target replacing Aichi 14, which currently focuses on protecting ecosystem services that contribute benefits to people. The following section builds on a number of existing policy statements in light of the findings of this review. Our policy pointers are primarily targeted at technical audiences involved in developing joint biodiversity and health targets. This may include academics, representatives from government, or those working in intergovernmental organisations.

The purpose of the pointers is to encourage efforts to address some of the uncertainties identified in this report. Here we draw on the report *Connecting Global Priorities: Biodiversity and Human Health: A State of Knowledge Review*, in offering the following policy pointers:

a) Awareness-raising and precautionary approaches

Those working in technical capacities (such as academics, representatives from government, or those working in intergovernmental organisations) may seek to raise awareness among policy-makers, business leaders and civil society organisations of the potential links between biodiversity and health, and the need for precautionary and "no regrets" approaches.

Some of the links between biodiversity and health remain poorly resolved, and in many cases, it may be premature to promote biodiversity conservation as a tool for protecting public health (Redford *et al.* 2014). Promoting poorly evidenced policy may waste resources, create undesired consequences and lock in maladaptation (Swanson et al. 2010; Juhola et al. 2016).

Nevertheless, when there is a convincing theoretical case that biodiversity, ecosystems and health are linked, but empirical evidence not yet established, then precautionary and "no regrets" approaches could be promoted. The precautionary principle argues against taking action if there is an uncertain risk of negative outcomes as a result of this decision. In an environmental context, it is often used to shift the burden of proof of the environmental impact of an activity onto those wanting to engage in the activity. The precautionary principle informs many international environmental agreements, such as the 1992 Rio Declaration (Principle 15) and the 1992 Framework Convention on Climate Change (Article 3.3, IUCN 2007). There are multiple approaches to operationalising the precautionary principle. For example, minimum safety standards based on population viability analysis has been suggested as one way of protecting species diversity when there is uncertainty about their future status (Hohl and Tisdell 1993). The precautionary principle has been criticised for being excessively risk-averse, inefficiently balancing potential benefits of action against risks and paralysing decision-making (Harris and Holm 2002). Moderate forms of the principle avoid many of the criticism of “hard” precautionary approaches (Hughes 2006). In some cases "no regrets" strategies – activities that have concrete net benefits, in addition to targeting uncertain primary objectives – may be a better option (Gray and Rivkin Jr 1991). We, therefore, argue that moderate precautionary and *"no regrets"* approaches to managing potential links between biodiversity and health should be promoted, without overstating poorly evidenced links between biodiversity and health. Nevertheless, evidence of those links does need to be developed, as discussed in policy pointer c).

Payment for ecosystem services for municipal water quality

At least US$36 billion is spent annually on over 550 payment for ecosystem service (PES) programmes globally (Salzman *et al.* 2018). Watershed PES schemes are the most common and developed of these, with around US$24.7 billion spent in 2015. There exist multiple PES models, with state, private and commercial actors operating as buyers, sellers and intermediaries (Vatn 2015). Watershed PES schemes where a single user compensated other parties to refrain from activities that harmed hydrological services or to engage in practices that improved those services, had an estimated market size of US$93 million in 2015 (Salzman *et al.* 2018).

One variation of this model focuses on urban service users. This model has been promoted by international conservation organisations. For example, The Nature Conservancy states that around 1.7 billion people live in large cities dependent on watersheds, and around 40% of watersheds experience moderate to high levels of degradation (Abell *et al.* 2017). They estimate that in one-in-six of 4,000 sampled cities, the cost of conserving watersheds would be equal or less than the savings in municipal water treatment. They argue that the number of cities with a positive return on investment in watershed conservation increases when additional co-benefits, such as climate mitigation, are commoditized (Abell *et al.* 2017). They specifically advocate for water funds, characterised by their use of a trust fund-like financial model to pay for hydrological services over long time periods (Goldman-Benner *et al.* 2012). Multi-institutional bodies, including a range of key actors, can independently govern these water trusts. Service users can include municipalities, businesses and other consumers. Investments are derived from the interest generated by the fund. These funds can be invested in a range of ways, but are typically directed towards watershed conservation, often compensating upstream actors for changing practices (Goldman-Benner *et al.* 2012). One motivation for promoting this type of PES initiative is the potential health benefits of improved water quality for urban users (e.g. Abell *et al.* (2017)).

b) Indicators for evidence-based decision-making

Those working in technical capacities in governments and intergovernmental organisations may encourage governments and business to refine and integrate health and environmental monitoring systems and indicators for evidence-based decision-making.

There have been calls to develop crosscutting indicators to monitor pressures, states and responses at the intersection between socio-ecological systems and health (WHO 2012a; CBD and WHO 2015). For example, the WHO advocated monitoring the number of countries implementing Integrated Water Resource Management to protect watershed services (WHO 2012b). Although in some cases, it may be necessary to develop new indicators, we suggest that structured decision-making processes should be used to select appropriate existing indicators. Structured decision-making processes emphasise understanding the decision context, defining objectives, developing alternative approaches to meeting objectives, estimate the consequences of those approaches, evaluating trade-offs, and then select and implement indicators to facilitate adaptive management (Gregory *et al.* 2012). Frameworks for selecting appropriate indicators have been developed, such as one proposed to assist businesses in choosing appropriate biodiversity indicators (Addison *et al.* 2018).

We suggest the need to develop frameworks for selecting suitable integrated biodiversity, ecosystem service and health indicators. This integration should involve explicitly identifying which populations are exposed to environmental change since beneficiaries are required for a potential ecosystem service to be realised. Answering questions at the interface between biodiversity and health often requires large amounts of spatially explicit data at relatively high resolution. This process could benefit from the use of both big data approaches and citizen science, as well as the integration of more diverse sources of information, such as from traditional knowledge systems (UNEP 2019). In addition, even when there are identified populations, it will also be important to evaluate the mediating factors that insulate against or exacerbate effects of changing environmental conditions.

Socio-ecological system complexity

The increasing use of mosquito nets as fishing gear (MNF) in malarial regions is predominantly viewed as a problematic, negative trade-off between short-term food security needs and risk of malaria transmission; with night-time protection from mosquitoes traded off for access to fish. In fact, the issue is far from straightforward and represents an example of a wicked problem traversing public health, food security and sustainability with a complex web of potential feedbacks (Short *et al.* 2019).

MNF may provide access to basic food and income needs for the very vulnerable. The importance of this access may be far greater in terms of health and well-being than its apparently simple contribution. Mosquito nets catch smaller fish which, when eaten whole, may provide disproportionately positive benefits in terms of micronutrients. This is particularly important for childhood development and resilience to diseases such as malaria. This effect may be enhanced when considering the high engagement rates of women in MNF; enabling maternal food provisioning which may further improve childhood access to nutrients and confer significant well-being advantages on the women themselves through social capital and the experience of autonomy.

Long term, concerns lie with sustaining these benefits alongside the increased harvesting of juvenile fish which MNF entails; this selective harvesting is viewed as undermining fish stocks and contravening conventional management methods. Indeed, the knock-on effects may threaten MNF-associated fisheries. MNF is widely illegal but generally takes place in areas where lack of enforcement capacity may be compounded by drivers of desperation and poverty, such that there is no ability to enforce rules. The indirect effects of poor health pull people into MNF; debilitating illnesses can drive engagement in lower effort and accessible fishing methods including MNF. Though these risks are serious, they remain unsubstantiated empirically. The benefits of MNF similarly remain unclear, yet represent opportunities for improved and more equitable health and well-being outcomes that it would be folly to ignore.

It may be more challenging to detect the indirect effects of socio-ecological change on health than the direct effects (see inset *Socio-ecological system complexity*). Nevertheless, these indirect effects may be substantial, and therefore there should be a careful choice of indicators to capture them (see inset *Choosing the right indicator*). For example, declining water quality may require households to invest in accessing improved water sources, which may reduce investment in improving other well-being domains (such as acquiring assets that might improve agricultural productivity). Our ability to detect and monitor these indirect pathways remains poorly developed. As a result, it may be valuable to support the development of monitoring systems that also account for these indirect pathways (as highlighted in pointer c).

Additionally, indicator data need to be collected at the appropriate spatial and temporal scale to track processes that exist at those scales (see inset *Socio-ecological system complexity*). For example, it may not be possible to detect how land-use changes affect health when using aggregated data over large geographical areas. Furthermore, indicators that can capture the cost of substitution and adaptation can reflect the true costs of environmental change on well-being, beyond simply looking at health outcomes.

Choosing the right indicator

Mosquito net fishing is increasingly recognised as an issue influencing multiple sustainable development goals and a potential source of conflict. Unfortunately, not only is a cross-sectoral response to the issue yet to be realised, but MNF may partially be driven by the influence of currently siloed policies (Short *et al.* 2019). From a public health perspective, this relates to an over-reliance on mosquito nets in anti-malarial efforts, coupled with "universal coverage" policies that may feed localised oversupply of nets, making them more available for alternative activities such as MNF. Similarly, policy responses from a fisheries management perspective have been to illegalise the activity with little regard for direct health and well-being impacts on those reliant upon it.

Negative impacts of these unilateral policies may be compounded by low detectability of unexpected feedbacks and/or failure, as exemplified by the recent turn around in global malaria reduction. This low detectability may be due to the use of indicators that are restrictive in their outlook. Current public health monitoring focuses largely on the sheer numbers of nets distributed and to a lesser extent utilised, recording these from a number of perspectives down to the household level. Explicit links between these *outputs* and the ultimate health *outcomes* are frequently lacking. More nets are therefore perversely seen to equal more success, missing the contribution net distribution makes to potential negative feedbacks. MNF exemplifies the need for a cross-sectoral "big picture" view when developing indicators of health outcomes, which considers mediating factors. In this case, these factors are mostly linked to poverty and include the dynamics of nutrition and well-being.

c) Key knowledge gaps

Those working in technical capacities may highlight the need for applied research to better understand the links between health and biodiversity.

This report identifies a number of key knowledge gaps that we believe are necessary to address:

- There exist few convincing estimates of the disease burden attributable to biodiversity change, at any scale. These estimates are important for demonstrating the potential importance of protecting biodiversity for health.
- Much of the evidence linking biodiversity, ecosystem services and health focuses on physical health. There are exceptions, such as the extensive body of research on the mental health benefits of nature exposure in developed economies. However, there are many other possible links between biodiversity and mental and social health that have not been explored.
- Understanding the role of functional diversity in ecosystem processes, and in the co-production of ecosystem services, over a range of temporal and spatial scales, is an active

area of research at the moment. We argue that understanding the role of functional diversity in generating ecosystem services will be important for understanding the links between biodiversity and health.

- There appears limited research exploring how biodiversity and health indicators could be integrated. In particular, there exists no framework for integrating existing indicators, which could be used to capture effectively the complex, spatially and temporally variable, direct and indirect linkages between ecosystem dynamics and human health.
- Although some evidence attempts to understand the direct links between ecosystem change, which may co-vary with biodiversity, and health, there is less research on the indirect links and the feedbacks between processes. This needs to include an explicit focus on the distributional effects of changes in biodiversity on health, with a focus on the impacts on vulnerable and marginalised groups.

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Appendix 1: The Conceptual Framework

The role of biodiversity in ecosystem processes

Biodiversity is the variety of life on earth (UN 1992). This variety of life is the "variability among living organisms […] and the ecological complexes of which they are part" (UN 1992). Biodiversity includes species, functional and phylogenetic diversity (Biswas and Mallik 2011). Species diversity is the number of species and their relative abundance (Hamilton 2005). Functional diversity is the range and distribution of what organisms do in ecosystems (Schleuter et al. 2010). Genetic diversity is the amount of variation in genetic information within and among individuals, species, or other ecological units (UN 1992b; UNEP-WCMC 2019). Biodiversity plays a fundamental role in regulating ecosystem processes (MA 2005; Dîaz et al. 2006; Mace et al. 2012). A large body of evidence suggests that, in general, greater species, functional and genetic diversity is associated with higher community productivity, stability and lower alien species invasibility (Tilman et al. 2014).

At least two dominant theories exist for why productivity may be greater at higher levels of species diversity (Loreau 2000). The first is that greater apparent productivity is the result of the "selection" effect; an area with more species has a higher chance of containing a single species that makes a greater individual contribution to community productivity than a random comparator (Huston 1997). The second is that greater productivity is the result of niche complementarity; differentiation of niches means that a community of complementary species uses available resources more efficiently (Tilman *et al.* 1997). A large body of evidence, from both experimental and natural settings, now indicates that niche complementarity results in greater productivity (Cardinale *et al.* 2012; Duffy *et al.* 2017). Although much of the research has focused on species diversity, there is also growing evidence that functional and genetic diversity are also associated with greater productivity (e.g. Fornara and Tilman 2008; Kotowska *et al.* 2010; Roscher *et al.* 2012; Bossdorf *et al.* 2013; Forrester and Bauhus 2016; Zhu *et al.* 2016).

There are many potential mechanisms through which biodiversity increases stability (Loreau and de Mazancourt 2013; Oliver *et al.* 2015). Generally, it is theorised that a diverse system is more likely to contain species or groups that persist during a disturbance, and more rapidly recover after perturbations, than a simpler one (Tilman and Downing 1994). A large body of evidence, mainly focusing on species but increasingly also functional and genetic diversity, indicates that biodiversity increases ecosystem stability (Tilman and Downing 1994; Girvan *et al.* 2005; Jiang and Pu 2009; Hector *et al.* 2010; Keith *et al.* 2010; Kotowska *et al.* 2010; Campbell *et al.* 2011; Pillar *et al.* 2013; Polley *et al.* 2013; Gross *et al.* 2013; Latzel *et al.* 2013; Majeková *et al.* 2014; Oliver *et al.* 2015; Venail *et al.* 2015; Mumme *et al.* 2015; Wang and Loreau 2016).

Greater biodiversity is thought to reduce the likelihood that an ecosystem is invaded by alien species (Tilman *et al.* 2014). It is theorised that more diverse communities have fewer available niches and fewer residual resources and so are less susceptible to invasion compared to communities with lower diversity (Tilman 2004). The "invasion paradox" emerged because of conflicting empirical evidence on the relationship between biodiversity and invasibility, with some studies finding a positive relationship, and others negative (Fridley *et al.* 2007). One explanation for the paradox is that the relationship depends on the scale of analysis, although one recent meta-analysis finds no support for this (Peng *et al.* 2019).

This literature appears to be biased towards studies in North America, plant communities, and experimental rather than observational studies. However, it appears that, generally, biodiversity increases ecosystem productivity and stability. Ecosystem productivity and its stability over time drive a vast array of ecological and biophysical processes (Cardinale *et al.* 2012). The links between biological processes, biological stocks, and the world's capital are discussed in the next section.

Linking ecosystem processes, biological stocks and capital

Within the conceptual framework, we now move away from discussing biodiversity towards processes downstream in the causal chain. The ecosystem processes discussed above constitute the earth's biological stocks (Mace 2019). We consider these processes not as final ecosystem services (discussed below), but intermediary steps that interact with other stocks to maintain natural capital (Carpenter *et al.* 2009).

Natural capital is the world's stock of natural assets that affect humanity (Dickie *et al.* 2014). Natural capital includes atmospheric, hydrological, pedological, geological and biological stocks. Biodiversity is a key contributor to biological stocks, which regulate the flux of energy, materials and information within a system, independently or in conjunction with other stocks (Costanza *et al.* 1997; Robinson *et al.* 2013; Jones *et al.* 2016).

Natural capital is considered as one of six types of the world's capital, which also includes human, produced, social, cultural and financial (Solesbury 2003; Jones *et al.* 2016) capitals, which are collectively referred to as human-derived capital (Box 1 in Figure 2).

The co-production of ecosystem services

The functioning of an ecosystem, and associated fluxes of energy, material and information, can contribute to the generation of services valuable to people. The following section describes how ecosystem services are generated through the interaction of stocks, including those nested under human-derived and natural capital (Figure 2). The MA defines four types of ecosystem service; provisioning, cultural, regulating and supporting (MA 2005). Provisioning, cultural and regulating services are final services since they directly contribute to human well-being. Although the MA describes "supporting services", there is a growing consensus that these should not be considered services at all since they underpin other services (Carpenter *et al.* 2009; Mace 2019). The role of biodiversity in maintaining ecosystem process has been referred to by some as "biodiversity services" (Seddon *et al.* 2016). Nevertheless, in the following, we include this role of biodiversity in "supporting services".

A recent review of 780 papers exploring how differing component of natural capital contribute to ecosystem services (Smith *et al.* 2017). The paper identifies the main attributes that influence the role of natural capital in ecosystem service production: vegetative cover; habitat for species or functional groups that provide a service; the characteristics of species or functional groups; biological and physical diversity; and abiotic factors that interact with biotic factors. Although these factors are linked, we can see that biodiversity is only one of several stocks within natural capital that affect ecosystem services.

Ecosystem services are often described as the flow of benefits from nature to people. However, much of the world is human-modified. People exist within socio-ecological systems where human and natural processes are closely linked, even when these systems do not spatially coincide (Berkes *et al.* 2000). There are several points within the conceptual framework where human and non-human factors interact to influence the flow of ecosystem services. First, *potential* or supplied services are produced through the interaction of stocks, including biological stocks where biodiversity is a key feature. Crucially, this includes the interaction of stocks found in both natural capital and human-derived capitals (Jones et al. 2016). For instance, ecological-agricultural systems combine both natural and artificial processes to produce food (The Economics of Ecosystems and Biodiversity (TEEB) 2018). Second, services only exist if there are people to receive them. Demand for the supplied service is required to turn a *potential* service into a *realized* one (Tallis *et al.* 2012). For instance, the demand for agricultural goods drives their production. Finally, additional human capital inputs are often required to utilize the ecosystem service (Jones et al. 2016). For example, infrastructure is needed to transport food from farms to people. Additionally, although biodiversity is described as a regulator of ecosystem processes, it can also be a direct source of final ecosystem services, such as the value of genetic diversity for bioprospecting or aesthetic values (Mace *et al.* 2012).

The interaction between stocks (nested within human-derived and natural capital) can harm as well as benefit people. This harm is sometimes referred to as an ecosystem disservice (Lyytimäki and Sipilä 2009; Von Döhren and Haase 2015). Some have argued that ecosystem disservices receive limited attention and are poorly defined (Shackleton *et al.* 2016). However, true ecosystem disservices are rare; many "disservices" actually emerge through the exploitation of one service at the expense of another, or the loss of a service (Chapin *et al.* 2000; Shackleton *et al.* 2016). For instance, a decline in agricultural pest-predators (a service) may increase populations of a range of pest species (a "disservice") (Chaplin-Kramer *et al.* 2011). The classification of services and disservices has been criticised as being overly simplistic and not reflecting underlying ecological complexity (Saunders and Luck 2016). For instance, an ecosystem function can generate both costs and benefits, such as in the case of some seed-eating birds that can reduce almond harvests but also limit the spread of almond disease (Luck 2014). The same service may also be a cost to some but a benefit to others. For example, believing that urban forests are attractive or unpleasant varies subjectively between people (Escobedo *et al.* 2011). As a result, classifying a function as a service or disservice depends on a variety of social, institutional and ecological factors (Rasmussen *et al.* 2017).

Health-related ecosystem services

Health is the state of physical, mental and social well-being (WHO 1946).[4] Ecosystem services may affect health in multiple ways (Box 3 in Figure 2, Bayles *et al.* 2016). Some final ecosystem services directly influence health. For example, forests can be a source of wild foods that contribute to dietary diversity (Ickowitz *et al.* 2014). Other final ecosystem services indirectly affect health outcomes – for instance, the regulation of pest-predators in agricultural systems that contribute to human nutrition (Chaplin-Kramer *et al.* 2011). The loss of these final services could lead to direct and indirect changes in human health (Corvalan *et al.* 2005). Supporting services do not themselves influence human well-being. However, they underpin the flow of final services (Corvalan *et al.* 2005). In this way, changes in supporting services may indirectly but fundamentally affect health. The links between ecosystem services and health are explored in more detail in the example of water quality regulation (see *Water quality and human health – Box 3 of Figure 3*).

Factors mediating the ecosystem service-health link

Several factors mediate the relationship between ecosystem service flow and health outcomes (Box 4 of Figure 2). First, changes in ecosystem service flows may only affect health if there is an unmet demand for that service (Myers and Patz 2009). For instance, a decline in the volume of water from a watershed will have a greater impact on those who are water stressed than those who are water secure. Second, a population may be able to substitute a declining ecosystem service, either with another ecosystem service or through technological and infrastructural adaptations. For instance, declining wild fisheries might be substituted by farmed fish (Merino *et al.* 2012). Finally, multiple mediating factors, such as behavioural change or institutional innovation, can insulate populations from, or expose them to, changes in a service flow (Myers *et al.* 2013). These mediating factors are partly determined by the capacity of actors to access and mobilise human-derived capitals. These factors are therefore strongly linked to social justice, which is discussed in more detail in *Distribution between groups*.

Change in the link between capital, ecosystem services and health

Configurations of stocks dynamically interact over time, causing variation in ecosystem service flows (Berkes *et al.* 2000; Price 2014). Change can occur at multiple points on the pathway between service production and a health outcome. Here we focus on changes in the co-production

[4] The expectation that normal functioning is a state of complete well-being has come under scrutiny, with some suggesting that health should relate to an individual's capacity to adapt to changing internal and external circumstances (Brüssow 2013).

of ecosystem services and feedbacks between health and those services. We are primarily interested in how changes in biodiversity, represented in biological stocks, may affect the co-production of services. However, these changes in biodiversity are often accompanied by changes in other stocks.

Altering the composition of stocks (nested in human-derived and natural capital) and their relationships with each other changes the flow of ecosystem services in multiple ways (Box 5 in Figure 2) (Villamagna *et al.* 2013). First, changing the composition of stocks may increase the flow of one service at the expense of another. For example, agricultural expansion into forests may increase stocks of human-derived capital but erode biological stocks, including biodiversity. As a result, the flows of agro-ecological services may grow to the detriment of hydrological services (Power 2010). Second, changes in the composition of stocks can also result in a trade-off of the flow of a single service over space or time (Rodríguez *et al.* 2006). For example, the planting of exotic tree species that are able to access water further underground than native vegetation might increase the short-term flow in water provisioning towards human needs, but at the same time would lower water tables, compromising long-term water supplies. Finally, stocks can also be combined synergistically, where the flow of multiple ecosystem services increases simultaneously. For example, one study in China found strong synergies between carbon sequestration and water interception (Qin *et al.* 2015). However, these “win-win outcomes” appear less common than situations where the flow of one ecosystem service increases whilst another declines (Howe *et al.* 2014).

For the most part, changes in the composition of different stocks lead to multiple service trade-offs and synergies, although these may manifest at differing rates over time, space and for different users (Tallis *et al.* 2008; Howe *et al.* 2014). Generally, it appears that more intensely modified systems, where there is a significant alteration of biological stocks, can simultaneously generate more benefits and more costs for people than less modified systems (Villasante *et al.* 2016).

There are also often multiple feedback processes that can dampen or intensify relationships within socio-ecological systems (Lambin and Meyfroidt 2010; Miller *et al.* 2012; Binder *et al.* 2013). For example, illness, attributable to ecosystem service changes may alter people’s livelihood strategies, ways they plan for the future, and physical capabilities (Fiorella *et al.* 2017). This may, in turn, change the flow of health-related ecosystem services. For instance, fishermen around Lake Victoria were more likely to engage in illegal or less sustainable fishing practices when ill (Fiorella *et al.* 2017). This unsustainable use may result in long-term nutritional health impacts. These feedback processes may represent additional important drivers of change within the system.

Interconnection between stocks
The above primarily discusses change as a consequence of trading off between stock nested within natural and human-derived capital, with an emphasis on the flow of ecosystem services that affect health. However, changes in some stocks can directly affect other stocks. For example, climate change is likely to affect many components of natural and human-derived capital, and their interactions (Bellard *et al.* 2012; Runting *et al.* 2017). For instance, changes in precipitation patterns and temperature may alter agro-ecological systems, with potential implications for human nutrition (Watts *et al.* 2015). However, these effects are likely to be highly context-dependent and challenging to generalize.

Distribution between groups and over scales

Distribution between groups

There is variation in the distribution of costs and benefits of changing ecosystem service flows between groups (Daw *et al.* 2011). Numerous factors can determine who "wins" and "loses" from changes in socio-ecological systems, including changes in biodiversity (Takeda and Røpke 2010; Daw *et al.* 2011; McShane *et al.* 2011).

In light of the growing concern about the social justice impacts of environmental degradation, it is valuable to consider the potential ways in which the health impacts of changes in biodiversity may be distributed between groups (Raworth 2012; Berbés-Blázquez *et al.* 2016). In our simple conceptualisation, power and capacities to mobilise capital shapes governance, access and control within socio-ecological systems, which can, in turn, exacerbate and perpetuate power asymmetries (Berbés-Blázquez *et al.* 2016).

Here we provide two examples of how power may influence the distribution of costs and benefits. First, some groups may have greater power to mobilize human-derived capital to generate private benefits but potentially also social externalities (Fisher *et al.* 2014). For example, agricultural expansion may increase dietary quality for upstream farmers, but compromise food security for downstream fisheries. Second, some groups may be less able to utilize human-derived capital to insulate themselves from changing ecosystem service flows (Myers et al. 2013; Fisher et al. 2014). For example, some individuals may be unable to afford alternative water sources in response to declining water quality. As a result, some groups may be less exposed to the health effects of socio-ecological change than others.

As well as the distribution of costs and benefits, recent environmental justice theory also recognises the need to interrogate decision-making procedures and recognise the status of different groups, values, and identities (Dawson *et al.* 2018). However, this is beyond the scope of this conceptual framework.

Distribution over spatial scales

The distribution of the costs and benefits of socio-ecological change varies between locations, as well as between groups at a particular location. Ecosystem services are produced at different spatial scales, and this can determine at what locations costs and benefits accrue. For instance, agriculture is a major driver of environmental change within the tropics (Song *et al.* 2018). International trade within increasingly globalized food systems can drive agricultural expansion (DeFries *et al.* 2010). This globalization of food systems has successfully increased food supplies worldwide (although impacts on health are mixed) (Kennedy *et al.* 2004). However, at a local scale, it can also lead to displacement, loss of locally important ecosystems services, and declining dietary quality (Power 2010; Lambin and Meyfroidt 2011; Gillespie and van den Bold 2017). Within their meta-analysis, Howe *et al.* (2014) note that trade-offs appeared to occur more often when actors were operating at local scales since this is the scale at which private interests are held. However, this finding might be a consequence of the challenge of attributing the effects of drivers on one scale to outcomes at another.

Distribution over time

There is also a growing concern that the current trajectories of development are increasing the flow of final services but harming the integrity of underpinning natural capital (MA 2005). In this respect, humanity may be trading-off the flow of final ecosystem services, which have facilitated significant improvements in human well-being in the short term, against the flow of those services in the long-term (Raudsepp-Hearne *et al.* 2010). This concern is supported by evidence suggesting that the flow of services has increased over time, but the state of natural capital is in decline (Shepherd *et al.* 2016). As a result, we may face intergenerational inequity as contemporary society benefits at the expense of future generations.

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