Pathways linking biodiversity to human health: A conceptual framework

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Version: September 2020

Highlights

- Biodiversity underpins human health as an essential life-support system
- We developed an integrated biodiversity-health framework
- Biodiversity influences health via pathways in four broad domains: reducing harm, restoring capacities, building capacities, and causing harm
- Both beneficial as well as harmful pathways link biodiversity with human health
- Understanding biodiversity-health pathways can inform nature-based solutions to public health

Abstract

Biodiversity is a cornerstone of human health and well-being. However, while evidence of the contributions of nature to human health is rapidly building, understanding of how biodiversity relates to human health remains limited in important respects. In particular, we need a better grasp on the range of pathways through which biodiversity can influence human health, including those that run through psychological and social processes as well as through biochemical and biophysical processes. Building on evidence from across the natural, social and health sciences, we present a conceptual framework organising the pathways linking biodiversity to human health. Four domains of pathways—both beneficial as well as harmful—link biodiversity with human health: (i) reducing harm (e.g. provision of medicines, decreasing exposure to air and noise pollution); (ii) restoring capacities (e.g. attention restoration and stress reduction); (iii) building capacities (e.g. promoting physical activity, transcendental experiences), and (iv) causing harm (e.g. dangerous wildlife, zoonotic diseases or allergens). We discuss how to test components of the biodiversity-health framework with analytical approaches and existing datasets. In a world with accelerating declines in biodiversity, profound land-use change, and an increase in non-communicable and zoonotic diseases globally, greater understanding of these pathways can reinforce biodiversity conservation as a strategy for the promotion of health for both people and nature. We conclude by identifying research avenues and recommendations for policy and practice to foster biodiversity-focused public health actions.

Keywords (6 max):

Biodiversity; Ecosystem services; Nature; Mediation; Public health; Human well-being

1. Introduction

Biodiversity comprises the diversity, abundance and identity of species, their genes and ecosystems, and underpins ecosystem services that are essential for human health and well-being (Cardinale *et al.*, 2012; Mace, Norris and Fitter, 2012; IPBES, 2019). However, biodiversity is declining at an unprecedented rate (IPBES, 2019), threatening the quality of life of all humans, rich and poor. Understanding of the specific aspects of biodiversity that are most relevant to human health and wellbeing, however, remains limited. Of the large body of research on nature and human health, in particular those that focus on health aspects derived through directly experiencing nature (e.g. Hartig *et al.*, 2014; Frumkin *et al.*, 2017), the majority of studies focus on the amount of nature, without distinction of ecological characteristics or quality (van den Berg *et al.*, 2015; Schwarz *et al.*, 2017; Collins *et al.*, 2020). We also acknowledge extensive research on how nature affects human health and well-being in ways that do not involve behavioural pathways, e.g. through provisioning or regulating ecosystem services, but these also often lack specifics on the biodiversity involved (Cardinale *et al.*, 2012; Sandifer et al 2015). Accordingly, we need to develop knowledge of whether and how biodiversity matters for human health (Marselle, Stadler, *et al.*, 2019b). A simplistic approach to measuring nature, for example the amount of greenspace, can serve as an important indicator for urban health planning goals, but it limits a clear understanding of how human health is influenced by the presence of, contact with, or change in biodiversity.

The importance of the fundamental linkages between biodiversity and human health, i.e. physical, mental and social well-being, is increasingly recognized by global and regional policy development (Corvalan *et al.*, 2005; Romanelli *et al.*, 2015; Ten Brink *et al.*, 2016; Korn, Stadler and Bonn, 2019). For example, the Convention on Biological Diversity (CBD) and the World Health Organisation (WHO) are collaborating to promote awareness of the influence of biodiversity on human health and well-being (Convention on Biological Diversity, 2016). In recent years, evidence has emerged that biodiversity is associated with physical health (Lovell *et al.*, 2014; Romanelli *et al.*, 2015; Aerts, Honnay and Nieuwenhuyse, 2018) and mental health (Lovell *et al.*, 2014; Korpela, Pasanen and Ratcliffe, 2018; Marselle, Martens, *et al.*, 2019). These studies show a direct relationship between biodiversity and human health outcomes. However, it is more likely that biodiversity will influence on human health indirectly, through causal pathways (Hough, 2014; Aerts, Honnay and Nieuwenhuyse, 2018).

A key research gap is, therefore, to unravel the specific causal pathways through which biodiversity affects human health (Clark *et al.*, 2014; Sandifer, Sutton-Grier and Ward, 2015; Aerts, Honnay and

Nieuwenhuyse, 2018). Some causal pathways are better understood (e.g. nutrition, infectious diseases, microbiota; Sandifer, Sutton-Grier and Ward, 2015; Aerts, Honnay and Nieuwenhuyse, 2018), than others (e.g. cultural goods and values; Clark *et al.*, 2014). This lack of a causal understanding of pathways linking biodiversity to human health limits application of nature-based solutions in public health, and subsequent influence on policy (Hough, 2014). In order to facilitate cross-sector policy and research integration on biodiversity conservation and public health (Korn, Stadler and Bonn, 2019), it is necessary to better identify and characterise the linkages between biodiversity and human health. A conceptual framework indicating the causal pathways through which biodiversity influences human health is needed for organising and guiding epidemiological and experimental health research. It should help to inform public health interventions, including nature-based solutions of biodiversity management for public health.

In this paper, we summarize the evidence linking biodiversity to human health and discuss the implications of this evidence for underlying causal pathways (for a detailed review of the literature, see Marselle, Stadler, *et al.*, 2019b). After defining biodiversity and health, we develop a conceptual framework for an understanding of biodiversity-health pathways, and then describe the four steps of our framework. We discuss how to test each step of the framework with analytical approaches and existing datasets. Finally, we identify applications in policy and practice and outline future research frontiers.

This conceptual framework relating biodiversity to human health, and the research it aims to organise and inspire, is intended to support the work of environmental and health researchers and professionals, including landscape architects and urban planners, natural resource managers, and the planned nexus assessment of the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES) on the interlinkages of biodiversity, water, food and health (https://ipbes.net/nexus). Importantly, we hope it can support implementation of the Agenda 2030 Sustainable Development Goals, the EU Green Deal, the WHO-CBD partnership, and the development of the CBD post-2020 global biodiversity framework and its translation into regional and national policies and associated measures.

Definitions

'Biodiversity' and 'health' mean different things to different people (IPBES, 2019). The definitions adopted here (Box 1 and Box 2, respectively) serve the identification of pathways linking biodiversity to human health. The definitions offer a platform for collaboration between different disciplines and professions for developing and applying knowledge about them.

Box 1. Biodiversity

Biodiversity is defined by the Convention of Biological Diversity (CBD) as “the variability among living organisms from all sources including, inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems” (United Nations, 1992). We use here biodiversity in a broad sense to include the composition, configuration and diversity of specific species or habitats, the abundance and biomass of species, the functional traits of species (e.g. nutrient content, medicinal properties, colours, sounds, contagious properties), and the genetic composition, and identity of particular species (e.g. lion, robin, ticks, oak).

In addition, there are two other broad and widely used, but different, concepts. *Nature* as defined by Hartig et al (2014, p.208) refers to “physical features and processes of nonhuman origin that people ordinarily can perceive, including the “living nature” of flora and fauna, together with still and running water, qualities of air and weather, and the landscapes that comprise these and show the influence of geological processes”. The term *Urban Greenspace* is defined as “all urban land covered by vegetation of any kind. This covers vegetation on private and public grounds, irrespective of size and function, and can also include small water bodies such as ponds, lakes or streams (“bluespaces”)” (World Health Organization, 2017c, p.2).

These broad terms can limit understanding of how variation in the ecological characteristics of the *Nature* or *Urban Greenspace* relates to health. *Biodiversity*, importantly, is more than just the amount of the *Nature* or *Urban Greenspace*, and refers more specifically to the details and qualities of living organisms and ecosystems.

Box 2. Health and Well-being

Health is defined by the World Health Organisation (WHO; 1948) as “a state of complete physical, mental, and social well-being and not merely the absence of disease or infirmity”. A bedrock of the WHO’s definition of health is not only the focus on factors that cause disease (pathogenesis), but also those factors that promote health and well-being (salutogenesis).

Physical well-being refers to the quality and performance of bodily functioning. This includes having the energy to live well, the capacity to sense the external environment, and experiences of pain and comfort (Linton, Dieppe and Medina-Lara, 2016).

Mental well-being refers to the psychological, cognitive and emotional quality of a person’s life. This includes the thoughts and feelings that individuals have about the state of their life, and a person’s experience of happiness (ibid).

Social well-being concerns how well an individual is connected to others in their local and wider social community. This includes social interactions, the depth of key relationships, and the availability of social support (ibid).

2. Conceptual Framework Relating Biodiversity to Health

2.1. Framework Precursors, Features and Functions: A User's Guide

The proposed biodiversity-health framework was generated during a three-day workshop in September 2019 with international experts from different disciplines, including biology, biomedical sciences, ecology, environmental epidemiology, environmental psychology, geography, medicine, modern literature, public health, and statistics, as well as experts from conservation agencies and health authorities. This Review article summarizes the discussions that consider the evidence linking biodiversity to human health from an interdisciplinary standpoint, focusing on the mediating pathways. In addition, we discuss the analytical approaches (Section 5) and data sets (Section 6) available to test the biodiversity-health framework, as well as recommendations for policy, practice and future research (Section 7). It is not intended to be an exhaustive review of the literature.

Consideration of other models, frameworks and approaches

We developed the biodiversity-health framework drawing from other published models. Three broad approaches linking the ecological environment and health are Planetary Health, One Health, and EcoHealth (Lerner and Berg, 2017; Buse *et al.*, 2018; Assmuth *et al.*, 2020). The simplest definition of Planetary Health is "the health of human civilisation and the state of the natural systems on which it depends" (Whitmee *et al.*, 2015). One Health and EcoHealth focus on a wider spatial scale and environmental determinants of health beyond biodiversity e.g. fossil fuel emissions (Whitmee *et al.*, 2015). This makes Planetary Health more suitable for the assessment of threats to health than understanding the mechanisms of the wider relationships between biodiversity and health (Lerner and Berg, 2017). One Health and EcoHealth are similar, both considering the interconnections between the health of humans, animals and ecosystems. One Health focuses on human and animal health (often domestic animals), with an emphasis on attaining optimal health through risk prevention (e.g. of zoonosis). EcoHealth concentrates on sustainability and achieving better human health through better ecosystem health (Lerner and Berg, 2017; Buse *et al.*, 2018). Whilst One Health and EcoHealth both consider biodiversity, it is not their primary focus, as it is in our framework.

Our approach differs from One Health and EcoHealth in that we conceptualise the type of contact between the individual and specific components of biodiversity, and the pathways leading to human health within the broader relationship. This enables us to place more emphasis on understanding how the different facets of this relationship work and their respective positive and negative aspects.

Further, biodiversity is considered in a number of existing conceptualizations of the relationship between the environment and health. As our focus was to ensure the biodiversity-health framework could be used to facilitate research on human health, the framework we put forward here builds upon previous conceptual models that identified causal pathways linking nature to human health (i.e. Hartig *et al.*, 2014; Frumkin *et al.*, 2017; Markevych *et al.*, 2017; Bratman *et al.*, 2019).

We also considered other models linking biodiversity to human well-being or quality of life, especially through the lens of ecosystem services (e.g. Millennium Ecosystem Assessment, 2005; Potschin and Haines-Young, 2011; Haines-Young and Potschin, 2012; Mace, Norris and Fitter, 2012; Díaz *et al.*, 2015). These models, however, were designed to serve a broad range of functions and audiences and to guide policy development, and – interestingly – human health is rarely considered explicitly as an outcome (Ford, Graham and White, 2015). As the specific pathways linking biodiversity to human health, however, are not directly identified in these models in such a way to facilitate health research, these models were not utilized.

Relationship to previous nature-health models

The Hartig et al. (2014) model of nature-health relationships identified groups of mediators through which the natural environment, and contact with nature, influences human health. The model distinguishes between nature and contact with nature to acknowledge the importance of peoples' encounters with nature and how they conceive of and experience it. Contact with nature is linked to four mediating pathways: air quality; physical activity; social contacts; and stress reduction. The model also acknowledges that the strength and direction of associations between nature and health may depend on individual characteristics (e.g. age, gender, genetics, socioeconomic position) and features of the broader context in which a person encounters nature (e.g. culture that may for instance lead visitors to a park to assign a particular meaning to some species observed there). The model put forward by Hartig et al. (2014) served as a review of extant research on already relatively well-described pathways, noting that although they had been addressed separately in different scientific and professional fields, they were likely to be intertwined and work together in various ways. However, the pathways were limited to only four groups of mediators, and the review did not seek to cover as-yet little-explored pathways.

To extend the representation of possible mediators, the Markevych et al. (2017) model of greenspace-health relationships details pathways in three broad domains by which greenspace could engender human health benefits. The three domains match to the three general functions of greenspace that relate to human adaptation: the ‘reducing harm’ domain relates to greenspace’s ability to mitigate stressor exposures; the ‘restoring capacities’ domain relates to the ability of greenspace to restore resources that have been depleted in efforts to cope with stressors; and the ‘building capacities’ domain relates to the use of greenspace for instoration of resources (or capacity-building) to better support coping. These three domains include Hartig et al.’s (2014) previously described pathways while also providing a means to organise them with novel pathways that might serve adaptation in similar ways. The Markevych et al. (2017) model did not distinguish nature from contact with nature.

The recently published Bratman et al. (2019) model specifically considers the effects of natural features, exposure and experience of nature have an impact on mental health. None of these existing models specifically addressed the different elements of biodiversity, or included the adverse influences of nature on human health.

2.2. Biodiversity and Health conceptual framework

Our biodiversity-health framework (Fig. 1) builds on the respective strengths of the models by Hartig et al. (2014), Markevych et al. (2017) and Bratman et al. (2019), while maintaining a focus on utility in health research. In this way, we draw on a wide array of methodological approaches and sources of data in order to address specific research questions and explore distinct pathways involving biodiversity.

Our conceptual framework shows how biodiversity, and contact with biodiversity, indirectly influences human health through four domains of pathways: (i) reducing harm (e.g. provision of medicines, decreasing exposure to air and noise pollution); (ii) restoring capacities (e.g. attention restoration and stress recovery); (iii) building capacities (e.g. facilitating physical activity, transcendental experiences); and (iv) causing harm (e.g. exposure to dangerous wildlife, infectious diseases or allergens).

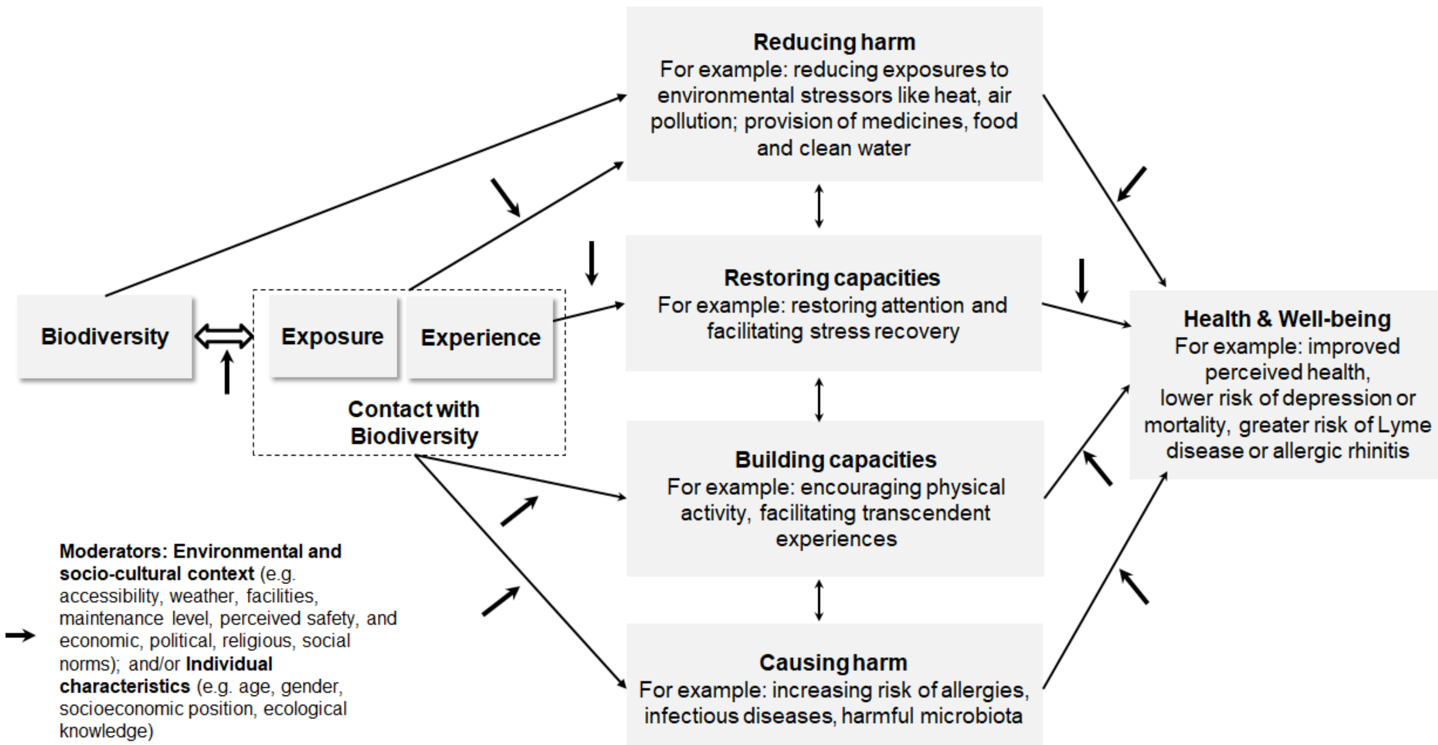

Fig. 1. The conceptual framework identifies pathways linking biodiversity to human health and well-being. The first pathway is contact with biodiversity, which considers exposure to and experience of biodiversity. Four domains of pathways linking biodiversity and health necessitate contact with biodiversity. An additional pathway links biodiversity directly to the reducing harm domain, which implies that biodiversity features may affect health without an individual or group having contact with biodiversity (e.g. biodiversity improving upstream water quality through bioremediation). Each domain may be related with all others (for ease of presentation, only adjacent relationships are shown). Two-headed arrows between the domains speak to reciprocal relationships. Associations between variables at the different steps are subject to modification by the environmental and socio-cultural context or individual characteristics as moderators.

Several novel features of our biodiversity-health framework warrant mention here. First, our framework focuses on the health effects of biodiversity rather than more general environmental entities (i.e. "nature" and "urban greenspace", Box 1). Biodiversity is considered with its different components and hence with all its complexity (Box 1). Each step of the biodiversity-health framework has a critical focus on these specific components of biodiversity which goes beyond previously conceptualized nature-health relationships. Second, the framework distinguishes between biodiversity and contact with biodiversity to acknowledge the importance of a person's exposure to and their experience of biodiversity. In addition, we also identify instances where biodiversity may influence human health without contact with biodiversity, particularly through the 'reducing harm' domain (see Step 3.1 below). Third, we include the domain 'causing harm' to represent the ways through which biodiversity can have a negative influence on human health. Representation of both beneficial and harmful effects gives a more complete picture of human relationships with biodiversity. Finally, the biodiversity-health framework references both the environmental and socio-cultural context and individual characteristics that can moderate relations at every step.

The present biodiversity-health framework refers to four intertwined domains of pathways that relate to human adaptation. Multiple pathways may work together simultaneously, with synergies and trade-offs. As such, it is important to consider how the effects realized through different pathways might stand in relation to one another, rather than treating them as independent (c.f. Zhao, Lynch and Chen, 2010; Dzhambov *et al.*, 2018, 2020). Consider the interrelationship between the two domains of pathways 'causing harm' and 'restoring capacities'. The COVID-19 coronavirus (SARS-CoV-2) is a dangerous, communicable zoonotic virus, most likely a result of contact with wildlife due to habitat loss (deforestation, agriculture, urbanization) (Taylor, Latham and Woolhouse, 2001; Yasuoka and Levins, 2007; Carrington, 2020). Consequences for individual and public health are severe, as COVID-19 can lead to death and collateral health damages by disrupting public health interventions such as vaccination and vector control programmes. During the COVID-19 pandemic lockdowns, in many countries people were still allowed to visit parks and other nature areas and did so more than before the lockdown (Venter *et al.*, 2020), indicating it fulfilled a need for psychological restoration. This intertwining of domains necessitates interdisciplinary research. Researchers in different disciplines have already begun to study processes as depicted here and can encourage other researchers to join their efforts.

Below we describe each step in the biodiversity-health framework. In Step 1, we discuss how to characterize and measure biodiversity. In Step 2, we define our first pathway, contact with biodiversity, as both exposure (Step 2.1) and experience (Step 2.2) of biodiversity. In Step 3, we describe the four domains of pathways through which biodiversity influences human health, namely: (i) reducing harm, (ii) restoring capacities, (iii) building capacities, and (iv) causing harm. In Step 4, we account for the human health effects of biodiversity.

Step 1. Biodiversity

This step characterizes the specific components of biodiversity that potentially influence human health and well-being (see Box 1). Depending on the health outcome studied (e.g. allergic rhinitis, depression), researchers may measure the appropriate tiers of biodiversity, genes, species or ecosystems (Box 1). For example, genetic diversity may be important for investigating allergic rhinitis, while species richness may be important for investigating depression.

Measurement of biodiversity

Biodiversity is currently measured in two ways: actual and perceived biodiversity (Fig. 2). Measurements of the actual biodiversity present at a location refer to the identity and number of species and individuals present and their functional characteristics, for example, the species richness, identity and abundance of street trees in a city district (see Supplementary Table 1). The amount of actual biodiversity that is present at a location will vary depending on the spatial extent of an area under observation (e.g. local, national, international) and the time of day and season of sampling (Kelling *et al.*, 2019). Accuracy will depend on sampling intensity (spatial and temporal extent), and previous knowledge and experience of the observer (Kelling *et al.*, 2019). Data on actual biodiversity can be gathered from a variety of sources (e.g. fieldwork, remote sensing) and operationalised in different ways (e.g. databases; for more information see Section 6).

Information on actual presence/abundance and trait values of species in an assemblage can be used to calculate measures of functional identity and diversity of the assemblage. Various parametric and non-parametric measures are available to assess actual species diversity or also genetic or functional diversity, with Shannon and Simpson Indices as common indices (Magurran, 2013). These assess the degree of heterogeneity, evenness or dominance within species assemblages.

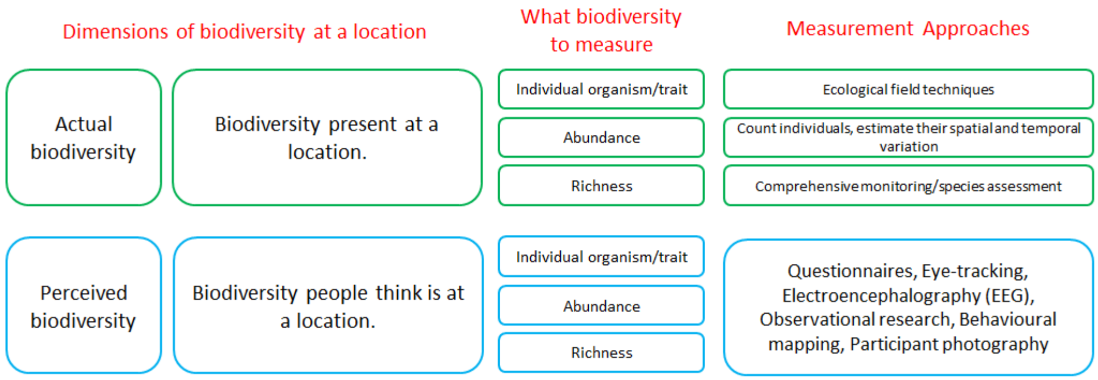

Fig. 2. Measurement of actual and perceived biodiversity.

When data on actual biodiversity are not available, a proxy measure may be used (Cameron *et al.*, 2020). The proxy measure, perceived biodiversity, is a person's subjective assessment of the biodiversity that they think is present in an environment (Fuller *et al.*, 2007; Dallimer *et al.*, 2012). Similar to actual biodiversity, perceived biodiversity may also refer to the identity and number of species (species richness) and individuals present (abundance) and their functional characteristics (Fig. 2). Perceived biodiversity is measured by asking people for their individual assessment of the species identity or richness in an environment through self-report questionnaires (Fuller *et al.*, 2007; Dallimer *et al.*, 2012; Marselle *et al.*, 2016; Southon *et al.*, 2018; Cameron *et al.*, 2020). Perceived biodiversity has stronger correlations with well-being than actual biodiversity (Dallimer *et al.*, 2012; Cameron *et al.*, 2020; Meyer-Grandbastien *et al.*, 2020). However, the proxy measure of perceived biodiversity cannot replace a measure of actual biodiversity (Hoyle, 2020). While perceived biodiversity assessments have been shown to be correlated with actual biodiversity measures (Fuller *et al.*, 2007; Southon *et al.*, 2018; Cameron *et al.*, 2020; Meyer-Grandbastien *et al.*, 2020), other studies have found no relationship between the two measures (Dallimer *et al.*, 2012; Shwartz *et al.*, 2014). Perceived biodiversity assessments may over or underestimate the amount of actual biodiversity in a location (Shwartz *et al.*, 2014).

Irrespective of how biodiversity is measured, we must also consider how these specific components of biodiversity result in various amounts of exposure to individuals or populations, and how people experience these measured biodiversity components. This is addressed in Step 2.

Step 2. Contact with biodiversity

Step 2 describes a person's contact with the components of biodiversity identified in Step 1. Here, contact with biodiversity is defined by two different aspects: exposure and experience. Exposure refers to a person's amount of contact with biodiversity. Experience refers to how a person experiences and interact with biodiversity.

Step 2.1 Exposure to biodiversity

To a greater or lesser extent, people are exposed to biodiversity throughout their daily lives. Here, exposure refers to the amount of contact that an individual or population has with biodiversity (Frumkin *et al.*, 2017; Bratman *et al.*, 2019). How exposure is measured is important for determining which causal pathways and health outcomes can be inferred (Nieuwenhuijsen, 2015). Exposure can be measured in one of two ways. The first is actual exposure to biodiversity, based on the frequency (how often) and duration (how long) a person or population has had contact with biodiversity (Shanahan *et al.*, 2015, 2016; Frumkin *et al.*, 2017). For example, two people live on the same street which contains a certain number and diversity of street trees (actual biodiversity, Step 1), but one person walks every day along the street while the other person only walks along the street once a week. The two persons have different exposure profiles (Frumkin *et al.*, 2017), and this difference is not captured solely in the measurement of the number and diversity of tree species (from Step 1). Data on frequency and duration of exposure can be obtained with smartphone apps that use ecological momentary assessment with location tracking (e.g. de Vries *et al.*, no date; MacKerron and Mourato, 2013; Beute, de Kort and IJsselsteijn, 2016; Tost *et al.*, 2019; Cameron *et al.*, 2020) or self-report questionnaires (e.g. Marselle *et al.*, 2015, 2016). Exposure to biodiversity can also be manipulated as a research design choice (e.g. Lindemann-Matthies and Matthies, 2018).

When data on actual exposure are not available, proxy measures are used (Bratman *et al.*, 2019). These proxy measures for assessing exposure to biodiversity are based on the amount of the components of biodiversity identified in Step 1 (Ekkel and de Vries, 2017; Bratman *et al.*, 2019). The first proxy measure is cumulative opportunity, which is the total amount of biodiversity surrounding a person's location (e.g. residence, workplace, neighbourhood) (Ekkel and de Vries, 2017). Data used to map actual biodiversity, such as from remote sensing and meta-genomics, can be used to determine the proportion or number of specific habitats, species or genes within the geographical area of interest (Dennis *et al.*, 2018; Donovan *et al.*, 2018). The second proxy measure is proximity, comprising metrics that estimate exposure as a function of the distance from one's location to the nearest environment with a specified minimum level of biodiversity (e.g. park; Ekkel and de Vries, 2017; Frumkin *et al.*, 2017; Bratman *et al.*, 2019). Walking distance from a residence to the nearest environment satisfying the minimally required level of biodiversity has also been used as a measure of proximity (Ekkel and de Vries, 2017).

The frequency and duration of exposure will have differential influences on the mediating pathways (e.g. stress of the ‘Restoring Capacities’ domain) (Step 3) as well as the health outcomes (Step 4) (Shanahan *et al.*, 2015). For example, short time periods of exposure (e.g. 2-5 minutes) to fish species richness (Cracknell *et al.*, 2016) and plant species richness (Lindemann-Matthies and Matthies, 2018) have been shown to reduce stress. Two hours of nature interaction per week might be beneficial for health and well-being (White *et al.*, 2019), but a single occurrence spent in long grass might be sufficient to become infected with Lyme Disease.

Step 2.2. Experience of biodiversity

Approaches to exposure measurement in Step 2.1 (e.g. frequency, cumulative opportunity) do not capture the experiential aspects of biodiversity exposure—what we term as the experience of biodiversity. It is important to recognise that people may experience biodiversity differently (Gaston, 2020), and these experiential characteristics of contact with biodiversity may be highly relevant for any health effects (Frumkin *et al.*, 2017). In this step, we consider the how biodiversity is experienced by people.

Firstly, humans experience biodiversity through the five senses (Frumkin *et al.*, 2017; Bratman *et al.*, 2019). The majority of the literature assumes vision as the primary sensory modality for biodiversity interaction (Conniff and Craig, 2016). The auditory (Hedblom, Knez and Gunnarsson, 2017), olfactory, somatosensory and gustatory senses may also be important to consider for their differential impacts on health outcomes (Franco, Shanahan and Fuller, 2017).

Secondly, experience includes an individual's interactions with biodiversity stimuli. One approach to classification of experience refers to degree of physical proximity with biodiversity is indirect or direct, and whether the type of interaction is incidental or intentional (Pretty *et al.*, 2005; Keniger *et al.*, 2013; Soga and Gaston, 2020). This classification results in four different experience types (see Table 1).

Experiences of micro-biodiversity are limited in this classification system. Direct contact with microorganisms is ubiquitous in all human environments, and humans are associated with a diverse microbiome (Grice and Segre, 2012; Gilbert *et al.*, 2018). However, the type of interaction with microbial biodiversity is usually incidental, as humans have limited abilities to experience microorganisms (Rieder *et al.*, 2017; Patel, Workman and Cohen, 2018). A notable exception is the direct, intentional interaction with micro-organisms when a person consumes microbial metabolic products (Liu *et al.*, 2018).

Table 1. Typology of people's experiences with biodiversity

	Type of interaction	
Degree of physical proximity	**Incidental** Experiencing biodiversity as a by-product of another activity	**Intentional** Experiencing biodiversity through direct intention
Indirect Experiencing biodiversity without being physically present in it	A person has no physical contact with biodiversity, and interaction is a by-product of another activity, e.g. video of an aquarium in the dentist waiting room (Clements *et al.*, 2019).	A person has no physical contact with biodiversity but interaction is intentional, e.g. viewing fish in an aquarium (Cracknell *et al.*, 2016), or trees through a window (Cox, Hudson, *et al.*, 2017; Cox *et al.*, 2019) or bird watching through a hide (Keniger *et al.*, 2013).
Direct Experiencing biodiversity by being physically present in it	A person is physically exposed to biodiversity, but the interaction is incidental to another activity, e.g., walking with others outdoors (Marselle *et al.*, 2015, 2016), driving along vegetated roadsides (Parsons *et al.*, 1998) encountering vegetation indoors (Bringslimark, Hartig and Patil, 2009) or working on a farm (Fontoura-Junior and Guimarães, 2019) or in a forest (Covert and Langley, 2002).	A person is physically exposed to biodiversity through direct intention (e.g. gardening, camping, birdwatching, conservation volunteering (Currie, Lackova and Dinnie, 2016).

To determine which of the four experience types a person or population is experiencing, one must measure both the physical proximity to biodiversity and the intention behind the behaviour. The degree of physical proximity (indirect or direct) can be specified in the research design. Researchers can design a study in which determines whether participants experience biodiversity through indirect contact (e.g. photographs, videos, Virtual Reality) (e.g. Chiang, Li and Jane, 2017; White *et al.*, 2017; Wolf *et al.*, 2017), or through direct contact (e.g. visits to a greenspace type with a certain level of biodiversity) (e.g. Fuller *et al.*, 2007; Dallimer *et al.*, 2012; Carrus *et al.*, 2015; Chang *et al.*, 2016). It is difficult to measure intentions objectively (Soga and Gaston, 2020). Thus, measuring intentions is best done by asking people about whether their intention to interact with biodiversity was intentional or incidental, or through a research design which manipulates the type of interaction (e.g. walking alone or with a friend, Johansson, Hartig and Staats, 2011; e.g. instructing participants to smell flowers, Colléony, Levontin and Shwartz, 2020). As a proxy measure, intentions could be assumed through human behaviour. For example, incidental interactions can be assumed when a person is running, walking with others, or playing with children outdoors, as experiencing biodiversity is a by-product of these activities. Similarly, intentional interactions can be assumed when a person is gardening, birdwatching, or conservation volunteering.

The experience type (Table 1) influences what a person experiences and the amount of biodiversity they 'absorb' (Frumkin *et al.*, 2017), which in turn may influence outcomes relating to the mediating pathways and health. For example, Carrus et al (2015) looked at the types of activities people were engaged, and how these activities affected restorative qualities, a mediator in the Restoring Capacities domain (section 3.2), and well-being. People who were contemplating the setting, walking or exercising in urban greenspaces of varying biodiversity had better well-being and experienced more restorative qualities than people who were reading, talking, or socializing with others (Carrus *et al.*, 2015). This suggests that perhaps a person whose interaction with biodiversity is direct-incidental (e.g. socializing with a friend in a biodiverse greenspace) experienced less well-being benefits because they were more distracted and less observant of the environment than a person, in the same location, whose interaction with biodiversity is intentional (e.g. contemplating the setting). As such, awareness might be an important aspect for interaction with biodiversity (Lin *et al.*, 2014; Soga and Gaston, 2020). This awareness can be tested through eye-tracking methods (Franěk, Petružálek and Šefara, 2019), neuroscience (Berman, Stier and Akcelik, 2019; Norwood *et al.*, 2019), participant photography or citizen science apps (Frumkin *et al.*, 2017).

The human health effects from exposure to and experience of biodiversity may occur through four domains of pathways. In moving from contact with biodiversity to human health effects, we need to consider these mediating pathways. This consideration is the focus of Step 3.

Step 3. Domains of pathways

The third step in the biodiversity-health framework describes the causal pathways linking biodiversity and human health. In Sections 3.1 through 3.4, we overview the four domains of pathways linking biodiversity to human health.

3.1 Reducing harm

Biodiversity can influence health and well-being by mitigating or reducing ill health. In this domain, we discuss the ways biodiversity contributes to the determinants of health—such as access to essential provisioning services, such as medicines, food and clean drinking water—as well as reducing harm caused by environmental stressors through regulating services (e.g. regulation of air and noise pollution or extreme heat) (Coutts and Hahn, 2015). Some pathways in this particular domain may not always require exposure to or interaction with biodiversity of the benefitting person or population (Fig. 1). The consumption or benefit from biodiversity´s service might be completely spatially distant from the origin of service (where the medical plant is growing or air quality is improved).

3.1.1 Medicinal drugs

Medicinal drugs derived from natural sources are one of the clearest examples of the importance of biodiversity for human health. Biodiverse environments provide natural products and genetic resources, which form the basis for both traditional medicine and modern pharmaceuticals (van Wyk and Wink, 2017). Medicinal plants are the primary source of natural product drugs for a majority of the human population (Romanelli *et al.*, 2015), and an estimated 70-80% of the global population depend on some form of traditional medicine for their primary health care (Ekor, 2014). Seventy-five percent of all antibacterial, antiviral and antiparasitic drugs approved by the United States have natural product origins (Newman and Cragg, 2012). Consequently, the prospective extinction of one million species (IPBES, 2019) may harm human health through the loss of medicinal plants and opportunity costs of forgone biomedical discovery (Chivian and Bernstein, 2008). To the best of our knowledge, no study has used mediation analysis to investigate whether the beneficial effects of biodiversity on human health can be explained by medicinal drugs.

3.1.2. Food provision

Good nutrition is fundamental for our physical well-being (World Health Organization, 2017a). Genetic and species diversity is essential for food production (e.g. Bernstein, 2014) and a well-balanced, nutritious diet. Ensuring biodiversity of foods is important for the development of potential food crops of the future, which may help ensure food security under threats of climate change (Bernstein, 2014) or intensive land use (Fahrig *et al.*, 2015). Biodiversity of crops and surrounding habitats can also reduce pest infestation, which in turn can reduce pesticide use (Petit *et al.*, 2015) to support the health of pollinators (IPBES, 2016) and people (Kim, Kabir and Jahan, 2017). Whilst food is a determinant of human health, to date, no study has explicitly tested whether nutrition mediates the associations between biodiversity and human health.

3.1.2 Reducing exposure to water health risks

Access to clean water is a necessity for human health (World Health Organization, 2019). Biodiversity plays a fundamental role in the provision and regulation of water quantity and quality. Much of the world's freshwater is provided downstream from mountains through river networks, and forests play an important role in flow regulation (Zhang *et al.*, 2017). Biodiversity is central to the health of these ecosystems, as it supports ecosystem functioning that provide, regulate and purify freshwater (Dudley and Stolton, 2003). The ability of wetland plants to remove heavy metals from water differs between species (Schück and Greger, 2020). A proxy indicator of good water quality and ecosystem health is the diversity and composition of aquatic organisms, as they are sensitive to nutrient pollutants in the water, such as nitrate (Cardinale, 2011), pesticides (Liess and Beketov, 2011) and pharmaceuticals (Binelli *et al.*, 2015). For example, freshwater molluscs (Ostroumov, 2005) or reed beds can contribute to clean freshwater by filtering water and controlling phytoplankton densities. In addition to the provision of freshwater, biodiverse environments can provide regulating ecosystem services that regulate severe flooding (Carter *et al.*, 2018), buffering of water scarcity (Ellison *et al.*, 2017) or landslides (Miura *et al.*, 2015).

3.1.3 Reducing exposure to air and noise pollution

Air and noise pollution are well known causes of negative human health outcomes (Basner *et al.*, 2014; Zivin and Neidell, 2018; Lelieveld *et al.*, 2019), particularly for urban dwellers. In locations where health-related standards are exceeded, the potential of tree and other plant species to regulate air pollutant concentrations and to mitigate noise can be especially important (Cohen, Potchter and Schnell, 2014; Haase *et al.*, 2014; Salmond *et al.*, 2016). There is also evidence that tree diversity has a significant impact on the potential to mitigate air pollution in cities (Churkina *et al.*, 2015; Grote *et al.*, 2016). Similarly, vegetation with higher structural complexity and density has been found to be an effective barrier to ultrafine particles from roads (Hagler *et al.*, 2012). Nevertheless, in the case of air quality, the tangible effect of urban vegetation is still under debate due to its complex chemical and physical interaction with the surrounding air depending on vegetation structure (e.g. planting density) and specific functional traits (e.g. leaf area, water-use strategy, pollen production) (Salmond *et al.*, 2016; Xing and Brimblecombe, 2019; Hewitt, Ashworth and MacKenzie, 2020). Some traits, such as allergenic pollen or volatile organic compounds may also negatively impact on health (see section 3.4.3). Regarding mediation, while air and noise pollution have been investigated as mediators linking nature to human health (e.g. Triguero-Mas, Donaire-Gonzalez, *et al.*, 2017; Bloemsma *et al.*, 2019; Crouse *et al.*, 2019), to date, no study has investigated whether air and noise pollution mediates the relationship between biodiversity and human health.

3.1.4 Reducing exposure to extreme heat

Human health is inevitably linked to the ambient temperatures to which populations are acclimatised, therefore deviations from non-optimum temperatures will lead to impacts on morbidity and mortality (Gasparrini *et al.*, 2015). Temperature extremes are one component of this health burden. Heatwaves already have the highest cumulative death rates of any extreme weather-related event in Europe (European Environment Agency, 2017)—disproportionately affecting older people, people with pre-existing health problems and people living in urban areas (Johnson *et al.*, 2004; Grize *et al.*, 2005; Poumadere *et al.*, 2005). Although extreme cold has been estimated to be more important than extreme heat, extreme heat is a particular concern for the future due to climate change, more people living in urban areas, and higher vulnerability (e.g. ageing populations) (European Environment Agency, 2017; United Nations Department of Economic and Social Affairs, 2019a, 2019b).

The design of cities can influence human exposure to extreme heat. Elevated land and air temperatures in urban areas are primarily due to the replacement of natural land covers with impervious cover with different thermal and structural properties (Oke, 1982; Gunawardena, Wells and Kershaw, 2017). The cooling properties of vegetation and water (from evapotranspiration and/or shading) mean that even modest amounts play an important role in temperature moderation and therefore influence human thermal comfort and the reduction of heat stress (Bowler *et al.*, 2010b). Vegetation abundance, structural characteristics, taxonomic diversity, species composition, functional diversity and functional identity are all known to affect the extent of cooling provided (Ziter, 2016; Schwarz *et al.*, 2017; Lindley *et al.*, 2019). For instance, tree traits (e.g. leaf area, pigmentation and canopy structure) influence how incoming solar radiation is intercepted (Speak *et al.*, 2020). Furthermore, evapotranspiration rates are determined by a range of species-dependent characteristics such as leaf area, canopy height and stomatal and hydraulic resistances, moderated by factors such as water availability (Gunawardena, Wells and Kershaw, 2017). Some of the shading properties important for cooling may also influence health impacts from other harmful exposures, such as non-melanoma skin cancers from excess UV exposure (Datzmann *et al.*, 2018). Despite evidence of the role of biodiversity for temperature regulation, to our knowledge, no study has used mediation analysis to investigate whether the beneficial effects of biodiversity on human health can be explained by reducing exposure to extreme heat.

3.2 Restoring capacities

The restoring capacities pathway refers to the recovery of adaptive capabilities that have been diminished through the demands of dealing with everyday life (Hartig, 2017). Over time, lack of restoration of these resources can lead to mental and physical ill health (von Lindern, Lymeus and Hartig, 2016). Environments that facilitate the restoration of these depleted resources are called restorative environments. Recent theorizing considers how experiences in natural settings, including contact with biodiversity, might figure in the renewal of relational and social resources (Hartig, 2020), but the currently conventional narrative about how nature experience produces restorative benefits centres on theories about the renewal of psychophysiological and cognitive resources used to mobilize and direct action.

3.2.1 Stress Recovery Theory

Stress recovery theory (SRT) considers that natural environments benefit health by facilitating recovery from stress (Ulrich, 1983; Ulrich *et al.*, 1991). Environments that facilitate stress recovery are those that evoke interest, pleasantness and calmness in a person. Evidence of restoration in SRT is through reduced physiological arousal, psychological stress, and negative emotions, and enhanced positive emotions (Ulrich *et al.*, 1991). Qualities of the natural environment that facilitate stress recovery are: moderate to high complexity; a focal point; moderate to high level of depth; a ground surface that is conducive for movement; a lack of threat; a deflected vista; and water (Ulrich, 1983). Consequently, qualities of the biodiverse environments that are considered a threat (e.g. large predators, snakes, spiders or stinging insects) could contribute to stress because they can cause a negative affective reaction (e.g. dislike, fear) and behavioural responses to avoid or escape the environment for personal safety (Ulrich, 1993).

In SRT, biodiversity is considered as a measure of an environment's complexity (Ulrich, 1983, p.96). Reduced physiological stress has been related to greater plant species richness (Lindemann-Matthies and Matthies, 2018). Greater afternoon bird abundances (Cox, Shanahan, *et al.*, 2017), and perceived plant species richness (Schebella *et al.*, 2019) have been related to reduced psychological stress. Positive emotions have been found to increase with increases in the diversity of forests (Johansson *et al.*, 2014), abundance of fish/crustaceans (Cracknell *et al.*, 2017), species richness of trees and birds (Wolf *et al.*, 2017), and perceived species richness of various taxa (White *et al.*, 2017; Schebella *et al.*, 2019). While stress has been investigated as a mediator linking nature to mental health (e.g. Triguero-Mas, Donaire-Gonzalez, *et al.*, 2017), to our knowledge, no study has tested whether stress, or negative or positive emotions mediate the relationship between biodiversity and health.

3.2.2 Attention Restoration Theory

Attention restoration theory (ART) focuses on components of environmental experience that allow for the restoration of the ability to direct attention (Kaplan and Kaplan, 1989; Kaplan, 1995; Kaplan and Berman, 2017). A person can restore their depleted ability to direct attention, when they experience four restorative qualities in an environment: (i) *fascination,* with stimuli in the environment that involuntarily attract and hold a person's attention without cognitive effort; *(ii)* experience of *being away* from everyday tasks or demands that draw upon directed attention; (iii) *extent,* with stimuli in the environment perceived as coherently organised and with sufficient scope to sustain exploration; and (iv) the experience of *compatibility* between the environmental setting and one's purposes and inclinations (Kaplan and Kaplan, 1989; Kaplan, 1995). Changes in cognitive tests after exposure to an environment are used as evidence of attention restoration in ART (Ohly *et al.*, 2016; Stevenson, Schilhab and Bentsen, 2018).

Biodiversity is not addressed in the theoretical writings of the ART (Marselle, 2019). However, natural environments providing specific components of biodiversity may be beneficial for attention restoration as they are likely to contain stimuli that facilitate the experience of *all* four restorative qualities (Korpela, Pasanen and Ratcliffe, 2018; Marselle, 2019). One study found restoration from directed attention fatigue was greatest for people who looked at images of urban greenspaces with high vegetation density compared to those who looked at urban greenspaces with medium- or low- density vegetation (Chiang, Li and Jane, 2017). This suggests that the effect of high vegetation density was most likely linked to abundance of plant species or their species composition. Perceived restoration—where people self-report changes indicative of restoration (e.g. feeling relaxed, refreshed after a long day) (Hartig, 2011)—has been found to be positively associated with actual and perceived landscape heterogeneity of urban greenspace (Meyer-Grandbastien *et al.*, 2020), vegetation structure and plant species of gardens (Hoyle, Hitchmough and Jorgensen, 2017), and actual (Wood *et al.*, 2018) and perceived species diversity (White *et al.*, 2017) of various taxa. The four restorative qualities have shown positive associations with structural complexity of urban greenspace (Scopelliti *et al.*, 2012; Carrus *et al.*, 2015) and perceived species richness of birds (Marselle *et al.*, 2016). To date, no study has tested the ability to direct attention as a mediator; only restorative qualities have been tested as a mediator of the relationship between biodiversity and health (Marselle, Martens, *et al.*, 2019). Restorative quality has been found to mediate the relationship between biodiversity of urban greenspace and general well-being (Carrus *et al.*, 2015). Restorative qualities *being away*, *fascination* and *compatibility* have been shown to mediate the relationship between perceived bird species richness and positive affect, and *compatibility* to mediate the inverse associations between perceived bird species richness and negative affect (Marselle *et al.*, 2016).

3.3 Building capacities

The building capacities pathway refers to the deepening or strengthening of capabilities for meeting everyday demands, rather than the restoration of a depleted resource (Hartig, 2007). In this domain we discuss how biodiversity can contribute to human via capacity building.

3.3.1 Encouraging physical activity

Physical activity is important for physical and mental well-being (Biddle and Mutrie, 2008; World Health Organization, 2018). Research suggests that physical activity in nature may produce greater physiological and psychological benefits than physical activity indoors (Bowler *et al.*, 2010a; Coon *et al.*, 2011) or in urban areas (Bowler *et al.*, 2010a). It has been shown that enhancing streetscapes by increasing biodiversity may promote physical activity (Säumel, Weber and Kowarik, 2016). Biodiversity loss of ash trees is associated with people spending less time on outdoor recreation (e.g. sport, exercise, walking)(Jones, 2016). Bjork et al. (2008) and de Jong et al. (2012) found a positive association between environments that were ‘lush’, i.e. rich in species, and greater self-reported physical activity, although others (Annerstedt *et al.*, 2012; Foo, 2016) could not find an association. While physical activity has been investigated as a mediator linking nature to mental health (e.g. Triguero-Mas, Donaire-Gonzalez, *et al.*, 2017), to our knowledge no study has investigated physical activity as a mediator of biodiversity-health relationships.

3.3.2 Facilitating social interaction

Social interaction is related to health and well-being (Holt-Lunstad, 2017). Biodiverse environments may provide a setting for social interaction with others, such as in neighbourhoods with more trees (Sullivan, Kuo and Depooter, 2004), or through conservation volunteering, where participants not only enjoy social interaction but also greater personal equality (Currie, Lackova and Dinnie, 2016). While previous studies have investigated social interaction as a mediator of nature and health (Ruijsbroek *et al.*, 2017; Triguero-Mas, Donaire-Gonzalez, *et al.*, 2017), only one study to date tested social interaction as a mediator of the association between parks with different levels of plant, bird and animal species richness and human health, and it did not find evidence for mediation (Foo, 2016).

3.3.3 Transcendent experiences (awe, humility, reflection)

Transcendent experiences—such as humility, awe (strong emotions of amazement and wonder; Ballew and Omoto, 2018), and reflection (thinking about one's life, goals and priorities; Kaplan and Kaplan, 1989)—contribute to well-being (Davis and Gatersleben, 2013; Capaldi *et al.*, 2015). Sights and sounds of nature, both mundane and awesome, have been found to elicit transcendental experiences (Capaldi *et al.*, 2015; Irvine *et al.*, 2019). Considering wilderness as a proxy for a biodiverse environment, studies have found that wilderness-based recreation can contribute to the ability to reflect about one's purpose and meaning in life, and the spiritual experiences of humility and awe (Irvine *et al.*, 2019). Qualitative research has shown that viewing some types of wildlife can contribute to a sense of humility and awe (Curtin, 2009). Quantitative research shows that the number of habitat types (Fuller *et al.*, 2007), and actual species richness of plants (Fuller *et al.*, 2007) and birds (Dallimer *et al.*, 2012) were positively associated with reflection. Perceived species richness of birds, butterflies and plants were also found to be positively associated with reflection (Dallimer *et al.*, 2012). To date, no study has tested whether transcendent experiences mediate the associations between biodiversity and health.

3.3.4 Promote place attachment and place identity

People may form emotional bonds, or place attachments, to biodiverse environments (Raymond, Brown and Weber, 2010; Ives *et al.*, 2017; Manzo and Devine-Wright, 2019). These emotional connections mean that these biodiverse environments could also form part of one's place identity (Manzo and Devine-Wright, 2019). Both place attachment and place identity are associated with psychological well-being (Manzo and Devine-Wright, 2019). Previous research has found that both place attachment and place identity were positively associated with the abundance of tree cover (Dallimer *et al.*, 2012), actual and perceived species richness of birds (Fuller *et al.*, 2007; Dallimer *et al.*, 2012), as well as perceived species richness of butterflies and plants (Dallimer *et al.*, 2012). Place identity was also found to be positively related to the number of habitat types and actual plant species richness (Fuller *et al.*, 2007). While, place attachment or place identity have been tested as mediators of the relationship between nature-health (e.g. Knez *et al.*, 2018), to our knowledge, no study has investigated whether the beneficial effect of biodiversity on health can be explained by place attachment or place identity using mediation analysis.

3.4 Causing harm

In this section, we illustrate some of the adverse effects that biodiversity can have for human health.

3.4.1 Contact with wildlife that cause harm

Research on contact with wildlife has traditionally focussed on negative aspects, such as injuries through contact with poisonous plants, mushrooms or berries, and large mammalian predators or reptiles (Methorst *et al.*, 2020). This includes e.g. attacks by large cats, bears or alligators, snake bites or skin irritation, when in contact with amphibia. Injuries can also be induced by plants, through skin contact (stinging nettles, algae; for allergens see 3.4.3) or poisoning through consumption, e.g. mushrooms. Dangerous interaction with wildlife may also cause mental and emotional harm, in addition to physical harm due to injury. Nevertheless, interactions with wildlife may also impact the restoring and building capacities domains with beneficial effects of wildlife on health (Methorst *et al.*, 2020).

3.4.2 Exposure to infectious agents causing human diseases

Serious infectious human diseases such as the recently emerged COVID-19 (pandemic), Ebola (West Africa), Borna (Germany) and the vector-borne diseases (VBDs)—such as malaria, dengue, zika, schistosomiasis, visceral leishmaniasis or tick-borne encephalitis—all stem from animals (World Health Organization, 2017b; Müller *et al.*, 2019; Ahmad *et al.*, 2020; Niller *et al.*, 2020). VBDs relate to very important aspects of biodiversity as they comprise an inter-relationship between pathogens (arboviruses, bacteria, protozoa), invertebrate vectors (i.e. mosquito, sand fly, tsetse fly, tick, snail, lice, flea) and host species (i.e. human, livestock, rodents, birds). The interactions of these three VBD components attribute to qualitative and quantitative biodiversity, for instance: genotype-specific replication in the vector (Riehle *et al.*, 2006); pathogen transmission to the host (Heitmann *et al.*, 2018); context-dependent host preference (Simpson *et al.*, 2012); differential responses in phenology and distribution (Elyazar *et al.*, 2013; Hasyim *et al.*, 2018); and dynamic pathogen spreading in social networks of host species (Ezenwa *et al.*, 2016).

Numerous studies have used mediation analysis to investigate whether there is a causal pathway between infectious disease agents and the level of biodiversity (genetic, phenotypic and species diversity of vectors/hosts, functional diversity for vector and reservoir competence)(Ostfeld, 2009; Roberts and Heesterbeek, 2018; Vadell, Gómez Villafañe and Carbajo, 2020). Evidence has been found for both the dilution hypothesis (increased biodiversity causes a decreased VBD prevalence; zooprophylaxis; e.g. Schmidt and Ostfeld, 2001) and amplification hypothesis (increased biodiversity causes an increased VBD prevalence, zoopotentation; e.g. Roiz *et al.*, 2019). But very often, no or weak relationships between biodiversity measures and VBD prevalence were detected (e.g. Stensgaard *et al.*, 2016; Ruyts *et al.*, 2018; Vadell, Gómez Villafañe and Carbajo, 2020). Certainly, the enormous complexity in biodiversity-health-environment interactions at local to global level is a major challenge when designing VBD prevention and vector control strategies. Nevertheless, biodiversity can also be part of the solution to combat VBDs by providing inspiration for new chemical and biological pesticides and pharmaceuticals and innovative genetic vector control tools (Famakinde, 2020; Kendie, 2020; Wooding *et al.*, 2020).

3.4.2 Exposure to microorganisms beyond infectious disease

Due to the potentially fatal effect of human-pathogenic microbes, the dominant public health objective is to limit contact with harmful microbes, through infrastructural and socio-cultural practices (e.g. sanitation and hygiene measures), or the use of pharmaceutical drugs targeting infectious microorganisms (Armstrong, Conn and Pinner, 1999). However, the human microbiome may also mediate positive effects of biodiversity on human health, as negative correlations between microbial or environmental diversity and the incidence of non-communicable, and in particular auto-immune, disease have been observed (Ruokolainen *et al.*, 2015; Mosca, Leclerc and Hugot, 2016; Aerts, Honnay and Nieuwenhuyse, 2018). Overall biodiversity decline can decrease microbiome diversity (Heiman and Greenway, 2016; Blum, Zechmeister-Boltenstern and Keiblinger, 2019; Johnson *et al.*, 2019; Ng *et al.*, 2019). To fully understand pathways mediating biodiversity effects on health, rigorous investigations of microbial exposure are required (Porras and Brito, 2019), as well as of the mechanisms of microbial protective diversity, e.g. dilution of pathogens (Libertucci and Young, 2019), improvements in metabolism (Adar, Huffnagle and Curtis, 2016; Visconti *et al.*, 2019) and regulation of the immune system (Kamada *et al.*, 2013; Belkaid and Hand, 2014; Mezouar *et al.*, 2018; Al Nabhani *et al.*, 2019; Zhang *et al.*, 2019).

3.4.3 Increasing exposure to airborne allergens and volatile organic compounds

Allergies have a major impact on people's health and quality of life (Baiardini *et al.*, 2006) and the loss of exposure to biodiversity may increase susceptibility to allergies (Prescott, 2020). The emission of biogenic particulate matter (spores and pollen) and volatile organic compounds (e.g. isoprene, a critical substance in O_3 formation) is species-specific (Peñuelas and Staudt, 2010; Grote *et al.*, 2016). Studies investigating whether allergenic pollen mediates the effect of biodiversity and health have found two different pathways. First, the biodiversity in an allergic person's microbiome is suspected to influence whether or not they will experience an allergic reaction (Haahtela *et al.*, 2013). Second, the abundance and species richness of allergenic plants can influence the opportunity for an individual to come into contact with allergenic pollen. While a large abundance of allergenic plants may affect allergic people negatively, a more biodiverse environment can protect through the dilution effect from exposure to allergenic pollen. However, a more biodiverse environment may also mean that a person is potentially exposed to a greater variability of allergens. Whether this leads to more allergies or protection from allergic sensitisation is still a matter of debate. For example, Hanski et al. (2012) showed that neighbourhood environmental biodiversity affects the composition of bacterial classes on people's skin, thus affecting allergy. The biodiversity hypothesis states that "contact with natural environments enriches the human microbiome, promotes immune balance and protects from allergy and inflammatory disorders" (Haahtela, 2019). Previous studies support the biodiversity hypothesis finding a more diverse environment is correlated with a healthy microbiome (Hanski *et al.*, 2012), and fewer allergic people (Haahtela *et al.*, 2013). Moreover, a highly biodiverse environment was found to be more protective against allergens, than the exposure to specific environmental allergens in early life (Von Mutius and Vercelli, 2010). This suggests that biodiversity in the environment may be protective against allergic response.

In terms of currently rising levels of atmospheric pollutants, new challenges for allergic people will rise as the composition and allergenicity of pollen can be altered (Beck *et al.*, 2013; Gilles *et al.*, 2018) and the skin barrier that is needed to protect from allergy development can be damaged by the influence of pollutants (e.g. O3 or NO2; Heuson and Traidl-Hoffmann, 2018). A higher biodiversity can also show a protective effect as it is shown that different tree species mitigate ozone levels at different seasons of the year and therefore guarantee a protection against high ozone levels for a considerable lapse of time (Manes *et al.*, 2012).

Step 4. Health effects

The fourth and final step in the biodiversity-health framework involves the assessment of human health and well-being effects that follow from the mediating pathways.

Measurement of health

Health (Box 2) is operationalised across three dimensions of well-being—physical, mental and social—to acknowledge the holistic biopsychosocial model of health (Engel, 1977; Fava and Sonino, 2008).

Biodiversity has been shown to affect all three dimensions of well-being (Irvine and Warber, 2002; Lovell *et al.*, 2014; Aerts, Honnay and Nieuwenhuyse, 2018; Marselle, Stadler, *et al.*, 2019b). Each dimension of well-being can be measured both objectively and subjectively (Table 2). Regarding subjective measurement of health, it is important to use existing valid, reliable questionnaires to assess well-defined clinical outcomes (Aerts, Honnay and Nieuwenhuyse, 2018), and ensure comparability with previous health research (Linton, Dieppe and Medina-Lara, 2016).

Table 2. Definitions of the three dimensions of health and well-being and examples of their objective and subjective measurement

	Measurement	
Health and Well-Being Dimension[1]	**Objective**	**Subjective**
Physical well-being refers to the quality and performance of bodily functioning. This includes having the energy to live well, the capacity to sense the external environment and experiences of pain and comfort.	e.g. mortality and morbidity; prevalence of a disease (or allergenic potential) within the population (e.g. COVID-19, malaria, dengue fever, plant allergies); medical doctor diagnosis of diabetes or hypertension	Self-report questionnaires on physical health
Mental well-being refers to dimensions such as the psychological, cognitive and emotional quality of a person's life. This includes the thoughts and feelings that individuals have about the state of their life, and a person's experience of happiness.	e.g. antidepressant prescriptions; psychiatrist diagnosis of depression or anxiety	Self-report questionnaires on quality of life, depression, anxiety, emotional state
Social well-being concerns how well an individual is connected to others in their local and wider social community. This includes social interactions, the depth of key relationships and the availability of social support.	e.g. number of people who volunteer in their local community; crime rates; observational research on social interactions	Self-report questionnaires on social well-being, e.g. the social well-being scale (Keyes 1998) or UCLA loneliness scale (Russell, 1998)

Note. [1] = All definitions from Linton, Dieppe & Medina-Lara (2016, p.12).

5. Considerations for statistical analyses

The causal pathways in the biodiversity-health framework can be tested through mediation models. Statistically, mediation models consist of a sequence of regression models in which the predictor variable, in this case biodiversity or contact with biodiversity, affects one or more intervening variables—a mediator within one of the four domains of pathways—which in turn affects human health. Investigation of inter-relationships between mediators of the four different domains involves multiple mediator models in which mediators are working in parallel or serial—rather than single mediators (Hayes, 2009; Dzhambov *et al.*, 2020). Analytical approaches recommended to test for mediation are the product-of-coefficients approach using ordinary least squares regression and bootstrapping, and structural equation modelling (for more information, see Dzhambov *et al.*, 2020).

Confounding variables

In a mediation analysis, confounding is a threat to validity, undermining the relationships between the predictor and outcome variables (Valente *et al.*, 2017). A confounding variable is a 'third' variable that is related to two (or more) variables in the mediation model that partially explains the relationship between these two variables (Valente *et al.*, 2017). Thus, confounding variables may influence the predictor-outcome relation, the predictor-mediator relation, or the mediator-outcome relations (Valente *et al.*, 2017). Identifying the potential confounders of the association between biodiversity, health and its mediating pathways is paramount to establishing the studied links clearly without biasing the study results or leading to erroneous conclusions. If no adjustment is made for these confounders, for example by including them as covariates in a regression analysis, then incorrect conclusions may be drawn about the plausibility of causal effects in the mediation model.

Biodiversity-health-pathways studies should consider the following confounders: gender, age, being part of a socially marginalized/privileged group (such as being from a certain ethnic group, race or socioeconomic group), or taking care of elderly, children or pets. Additional confounders in biodiversity-mental health studies are perceived naturalness, visual complexity and amount of nature in general (de Vries and Snep, 2019). Moreover, specific study contexts may require consideration of other confounders such as area socioeconomic status, degree of urbanization, area deprivation or neighbourhood gentrification stage (Cole *et al.*, 2019), livestock rearing (Hasyim *et al.*, 2018), weather, or study design factors like sampling order in experimental study designs (Triguero-Mas, Gidlow, *et al.*, 2017). Statistical methods such as Bayesian network modelling can be a reasonable way to select a minimum sufficient set of confounders.

Modifying variables

The strength or direction of the relationship between biodiversity and human health via any of the four domains of pathways is subject to modification by the environmental/socio-cultural context and individual characteristics (Fig. 1). As detailed in Figure 1, moderating factors can influence the relationships between biodiversity (Step 1) and contact with biodiversity (Step 2), and between contact with biodiversity (Step 2) and each of the four domains of pathways (Step 3), and the influence of pathways within each domain (Step 3) on health and well-being (Step 4).

At any steps in the conceptual model, and depending on specific research aims and research questions, researchers may explore variables relating to the environmental/socio-cultural context and individual characteristics. For example, individual characteristics such as age, gender or socioeconomic position may be of interest. These moderator analyses ensure that potential differential effects and pathways by population subgroups are understood and that any intervention is socially just. Moderating factors relating to the environmental/socio-cultural context and individual characteristics have all been found to influence nature-health (Triguero-Mas *et al.*, 2015; Jones, 2016; Van den Berg *et al.*, 2016; Triguero-Mas, Donaire-Gonzalez, *et al.*, 2017; White *et al.*, 2017; Zijlema *et al.*, 2017; Cole *et al.*, 2019) and biodiversity-health relationships (Carrus *et al.*, 2015; Wheeler *et al.*, 2015). These same personal and environmental context variables may also moderate the biodiversity-health pathways.

Measurements of both actual and perceived biodiversity (Step 1) are influenced by knowledge and experience. Actual biodiversity measurements are dependent on the knowledge of, e.g. highly trained experts to identify species and count abundances with specialized technologies or prior experience of particular sites (Kelling *et al.*, 2019). People who have better biodiversity knowledge also tend to be more accurate in their perceived biodiversity assessments (Dallimer *et al.*, 2012; Southon *et al.*, 2018).

Factors relating to the environmental/socio-cultural context and individual characteristics may influence whether a person is exposed to specific components of biodiversity (Step 2.1), and the ways in which people experience biodiversity—the relationship between biodiversity and contact with biodiversity (Step 2.2; Fig. 1)(Frumkin *et al.*, 2017). Exposure to biodiversity may be encouraged or discouraged through aspects of the environmental/socio-cultural context, for example amenities (e.g. public toilets), park programming (Hunter, Cleary and Braubach, 2019; Vierikko *et al.*, 2020), accessibility and maintenance status of the space where biodiversity is found, perceived safety in the space where biodiversity is, and other space-related variables such as size, type, land ownership (that can also be considered confounders)(Bratman *et al.*, 2019). Individual characteristics, such as personal time demands, transport corridors, may also influence exposure (Bratman *et al.*, 2019). Experience of the specific components of biodiversity will be influenced by individual characteristics such as connectedness to nature, and preference about, knowledge of, perception of (including fear of certain species), attitudes towards, receptivity towards, or childhood experiences of biodiversity (Wells and Lekies, 2006; Bratman *et al.*, 2019). Moreover, the socio-cultural context, such as values around biodiversity (King *et al.*, 2017; Bell *et al.*, 2018; Chan, Gould and Pascual, 2018) can also affect the experience of biodiversity (Bratman *et al.*, 2019).

6. Data sources available to assess biodiversity, health and the mediators in the four domains

To operationalise the model and allow for application in testing of the biodiversity-health framework in health research and application, in this section, we identify available data sources. Supplementary Table 2 details these possible data sources.

6.1. Step 1: Biodiversity

Data on actual biodiversity (Step 1) exist on local to global geographical scales. These data can be in the public domain but are often “hidden” within administrative agencies, museums, research institutes, etc. (Beck *et al.*, 2012). An increasing number of initiatives now combine biodiversity data from across the globe into (partly) open databases (e.g. GBIF: The Global Biodiversity Information Facility, 2020) or at the national scale in Atlases (e.g. German Atlas for Flowering Plants and Ferns, Bundesamt für Naturschutz, 2013)(see Supplementary Table 2). These data repositories are highly heterogeneous in structure or quality, and often biased both taxonomically and geographically, such as towards the Global North, charismatic species and aboveground terrestrial biodiversity (e.g. Titley, Snaddon and Turner, 2017; Troudet *et al.*, 2017; Cameron *et al.*, 2018). This bias might limit or even misguide our understanding of biodiversity-health pathways. Remote sensing provides opportunities for reducing bias by assessing, for example, e.g. land cover, plant structural diversity or plant functional traits (Lausch *et al.*, 2016; Dennis *et al.*, 2018). The use of eDNA and meta-barcoding (Ji *et al.*, 2013) can also help to support field biodiversity assessments.

6.2 Step 2: Contact with biodiversity

Assessment of exposure (Step 2.1) to actual biodiversity can be assessed using measures to determine a person's frequency and duration of contact with these habitats. Proxy measures of cumulative opportunity or proximity to these habitats can be applied. To obtain data on actual exposure new data might need to be collected, for example with study design in which participants are randomly assigned to spend a certain amount of time in different sample plots in which an ecological survey has been conducted (e.g. Chang *et al.*, 2016; Lindemann-Matthies and Matthies, 2018). Assessment of experience to actual biodiversity (Step 2.2) would require self-report, observational research or research design in which participants are assigned different degrees of physical proximity and intention.

6.3. Step 3: Assessment of mediators in the four domains

Many data sources on the four domains (Step 3) exist, which can support the analysis of biodiversity-health relationships and mediating pathways. For the 'Reducing Harm' domain, open-access environmental data comprise, for example, local noise exposure information in European metropolitan areas, provided by the European Environment Agency, or Local Climate Zones (LCZs) for urban climatology (Stewart and Oke, 2012; Demuzere *et al.*, 2019). Remote sensing can deliver information on land surface temperatures (e.g Zheng, Myint and Fan, 2014; Kremer *et al.*, 2018) and air quality (Gupta *et al.*, 2006).

Datasets for the 'Building Capacities' and 'Restoring Capacities' domains range from the local scale in city-wide health studies (e.g. Nieuwenhuijsen *et al.*, 2014), to the district-level in national surveys (e.g. the Monitor of Engagement with the Natural Environment), and the regional scale in medicinal plants databases (Babu *et al.*, 2006). Access to local scale datasets will need to be requested; while data at coarser spatial resolution are often publicly available. However, depending on the specific mediators investigated (e.g. attention restoration, place attachment), researchers may need to collect new empirical data.

Data for the 'Causing Harm' domain may be available—usually upon request—at the local scale in health cohorts for the human microbiome, regional and national scale for allergenic pollen, or at the international scale for distribution of ticks and mosquitos (see Supplementary Table 2). Ground observation, remote sensing and genetic biodiversity monitoring can be used to determine the presence, abundance, density and functional traits of invasive, pest and allergenic biodiversity (Skjøth *et al.*, 2013).

6.4. Step 4: Human health effects

Human health data (Step 4) exists on local to global scales. As health data contain highly sensitive, personal information, strict ethical rules apply regarding confidentiality and anonymity. Consequently, individual-level data at the local level are not in the public domain. However, for research purposes, it is often possible to request access to these existing health datasets, for instance doctor or hospital records. In these cases, researchers must submit an official request to the data holder. Publicly available health data are aggregated at larger geographical scales, such as at county or state level (e.g. US CDC Behavioral Risk Factor Surveillance System, Jones, 2017; German Socio-Economic Panel (SOEP), Goebel *et al.*, 2019). Global human health data are often open access (see Supplementary Table 2).

7. Recommendations for policy, practice and future research

7.1 Policy implications

The increasing relevance of biodiversity for health and well-being is reflected both in the scientific arena with increasing work on EcoHealth, Planetary Health or OneHealth, and the policy arena (IPBES, 2019; Korn, Stadler and Bonn, 2019). Human health already figured prominently in the 2005 Millennium Ecosystem Assessment (Corvalan *et al.*, 2005), and an increasing range of UN actors have adopted respective resolutions addressing human consequences of biodiversity loss—specifically the UN Decade on Biodiversity (2011-2020), and the Sustainable Development Goals (SDGs). The EU Green Deal has a specific objective to preserve and restore ecosystems and biodiversity (European Commission, 2019). Since 2015, the WHO has collaborated with the CBD to foster the work on health impacts of biodiversity (Romanelli *et al.*, 2015). The IPBES is presently scoping a global nexus assessment on the links between biodiversity, water, food and human health. While progress is being made to link the biodiversity and public health sectors (Keune *et al.*, 2019), "silo-thinking" is still common. To implement actions, policy frameworks are needed to assure that health and well-being is included as integral components to biodiversity conservation policies (Korn, Stadler and Bonn, 2019). Likewise, biodiversity should be considered in public health, and spatial and urban planning policies. The current discussions on the CBD post-2020 global biodiversity framework, the forthcoming IPBES nexus assessment and the EU Green Deal provide pertinent leverage points to strengthen the biodiversity-health policy agenda. Biodiversity-related public health threats can only be solved by integrating health and environmental perspectives. The provided biodiversity-health framework may provide clear guidance for this multisectoral and multidisciplinary dialogue.

7.2 Practice implications

The concept of nature to promote public health is longstanding, championed by Florence Nightingale, and the creation of hospital gardens, public parks (Wheater *et al.*, 2007; Ward Thompson, 2011; Hickman, 2013), and allotment gardens (van den Berg *et al.*, 2010). Presently, the use of natural environments is considered as a health promotion intervention (Irvine and Warber, 2002; Maller *et al.*, 2005; World Health Organization, 2016; Frumkin *et al.*, 2017). The asset-based approach to health has led to the development of a person- and asset-based 'social prescribing' movement, whereby non-medical interventions are provided to promote health and alleviate the pressure on acute medical care facilities (Polley *et al.*, 2017). Social prescriptions can include nature-based interventions (Cook, Howarth and Wheater, 2019), such as outdoor walking groups (Marselle *et al.*, 2015, 2016; Irvine *et al.*, 2020), forest-bathing or horticulture-based therapies (e.g. https://www.adoseofnature.net/). We suggest that physicians and public health authorities may consider prescribing biodiversity-based interventions to bring humans into contact with biodiverse environments, such as nature conservation activities (Pillemer *et al.*, 2010).

The provided biodiversity-health framework can help inform natural resource managers in developing and maintaining their protected areas or urban parks for both people and biodiversity conservation (Davies *et al.*, 2019; MacKinnon *et al.*, 2019). Public health implications of biodiversity-health relationships can foster the application of nature-based solutions as public health infrastructure by urban planners and landscape architects (Heiland, Weidenweber and Ward Thompson, 2019; Hunter, Cleary and Braubach, 2019).

7.3 Recommendations for future research

Fundamentally, the functionality of the biodiversity-health framework lies in its capacity to orient attention to considerations of importance for understanding relations between biodiversity and health. These include but are not limited to the following: the need to consider (i) biodiversity in its complexity including the diversity, identity, abundance of species, genes and ecosystems; (ii) the distinction between actual and perceived biodiversity, (iii) how biodiversity can influence health via multiple pathways, many of them necessitating interaction or contact with biodiversity, (iv) how pathways can intertwine, on one level and across levels, and (v) how environmental/socio-cultural contextual factors and individual characteristics can modify links between components of the biodiversity-health framework.

The presented conceptual framework provides a causal understanding of biodiversity-health linkages. Naturally, like its precursors (Hartig *et al.*, 2014; Markevych *et al.*, 2017; Bratman *et al.*, 2019), the biodiversity-health framework does not aim to represent all the complexity of real-world situations. We have tried to strike a balance between representation of complexity and the utility of the framework as a guide to communication, research, and practice. For example, we represent the possibility of reciprocal relations and feedback between components of the biodiversity-health framework, but not as comprehensively due to space limitations. And yet, the framework is not simplistic, as we represent the multiple levels on which intertwined processes can run between biodiversity and health and the sets of moderators of those pathways.

By providing a causal understanding of biodiversity-health linkages moving from biodiversity (Step 1) to contact with biodiversity (Step 2) to the four domains of pathways (Step 3) to human health (Step 4), we show avenues to operationalise research to test the framework, with available data resources and analytic approaches. The biodiversity-health framework thus supports further collaboration by researchers trained in different disciplines who have already begun to study processes as depicted here and who can enlist other researchers to join their efforts. Some research questions might not appear in the visual and textual presentation of our biodiversity-health framework due to brevity, which does not mean that we consider them unimportant.

The next steps for research are to operationalise this biodiversity-health framework. Using the biodiversity-health framework, we hope to inspire future researchers to specifically investigate these mediating relationships. In the short-term, the fields of biodiversity and public health could be fostered by focussing on testing the two sides of the biodiversity-health framework separately: assessing the relationship between biodiversity (Step 1) or contact with biodiversity (Step 2) and a specific mediating variable (e.g. physical activity, Step 3); and assessing the relationship between the same mediating variable (e.g. physical activity) and human health (Step 4). Most importantly, data-driven experimental research approaches employing longitudinal, intervention and randomized controlled trial experimental studies in the field and the lab are needed to test these conceptual pathways and their synergistic interaction to understand biodiversity-health linkages (Aerts, Honnay and Nieuwenhuyse, 2018; Marselle, Stadler, *et al.*, 2019a; Müller *et al.*, 2019).

An important research frontier is to further our understanding of how we experience biodiversity (Gaston *et al.*, 2018). This may then influence how we ultimately value (Chan, Gould and Pascual, 2018) and shape our interaction with biodiversity—both for developing conservation and enhancing human health. We need to understand the shape of the relationships between specific elements of biodiversity (i.e. the richness and abundance of species, their identity, their behaviour, and their traits, as well as genetic and ecosystem diversity) and human health outcomes. When analysing pathway mechanisms, it is crucial to assess how the environmental and socio-cultural context and individual characteristics may moderate the outcomes. Overall, more research is needed on people's contact with biodiversity (step 2)(Gaston, 2020). More research is needed on how differential exposures to biodiversity (Step 2.1) influence human health, in order to unravel 'dose-response' relationships. Future research into the biodiversity-health framework could usefully investigate whether the four different types of experience with biodiversity (Step 2.2) influence the mediating pathways in the four domains. This understanding will then inform how to better promote or—in case of the 'causing harm' domain—possibly avoid harmful contact with biodiversity for human health.

Future studies can investigate how to implement these findings in urban and rural landscape planning considering synergies and potential trade-offs as well as nature-based solutions to public health interventions and conservation action. Public health and conservation interventions need to be evaluated in real-world situations to develop and share best practice. This includes cost-benefit and other economic analyses of the effectiveness of different interventions, since (complementary) nature-based health interventions may significantly contribute to reducing health care costs for non-communicable diseases, such as depression. The benefits then need to be publicised and well communicated to decision makers to flow into policy design as well as into individual behavioural choices. Scenario building and statistical modelling can assist in forecasting the effects of further biodiversity losses or gains for human health and thereby inform management priorities. Here, joint working should be sought with ongoing efforts of IPBES in scenario modelling to help foster informed decision making as well as appropriate indicator development to monitor trends to adapt management and policy accordingly.

Conclusion

We present a new conceptual framework to serve as the basis for strategic discussions and better alignment of biodiversity-health research, policy and practice with respect to public health, environmental psychology, landscape and urban planning as well as biodiversity conservation. The biodiversity-health framework draws on diverse forms of knowledge to elucidate a range of causal pathways linking biodiversity and health and, importantly, depicts the biodiversity that people can experience in their everyday lives. As such, the awareness of the breadth of effects biodiversity has on human health necessitates a large range of approaches to protect and restore biodiversity to promote health—starting in gardens and parks, over biodiverse agricultural areas to tropical forest, wilderness and nature reserves. Here, we provide a tool in order to explore explicit management options in a standardized and comprehensive manner and a given geographical context. Our biodiversity-health framework should therefore serve a broad range of purposes, including identification of health indicators and interventions, formulation of policy, and communication among diverse groups of audiences.

The COVID-19 pandemic brought biodiversity into the limelight. It showed how harming biodiversity through illegal trade or habitat destruction can lead to severe health impacts, and how enjoying urban nature was important for people's health and well-being in lockdown. We now urgently need to further our understanding of salutogenic benefits and pathogenetic burden of biodiversity. The current joint working of WHO and CBD needs to be supported and enshrined in the up-coming post-2020 global biodiversity framework and respective targets for policy and management. Fundamentally, investment into biodiversity conservation and restoration needs to be viewed as investment into our human health.

Author contributions

Conceptualization: Marselle and Bonn developed the idea for the work and organised the workshop where the concepts and biodiversity-health framework were created with all authors.

Project administration: Marselle and Bonn led management and coordination of writing with support from Cox, de Bell, Hartig, Knapp, Lindley & Triguero-Mas.

Writing - original draft: Marselle, Braubach, Cook, Cox, de Bell, Hartig, Heintz-Buschart, Irvine, Kabisch, Knapp, Kolek, Krämer, Lindley, Martens, Müller, Potts, Stadler, Warber & Bonn.

Writing - review & editing: All authors.

Funding acquisition: Marselle & Bonn.

Acknowledgements

The Expert Workshop was funded by the Volkswagen Foundation [grant number 96 067]. MRM, AB and AHB were funded by the German Centre for Integrative Biodiversity Research (iDiv) Halle-Jena-Leipzig of the German Research Foundation [FZT 118]. TH received financial support from the Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning [grant number 2016-01157]. MTM is funded by a Juan de la Cierva fellowship [grant number FJCI-2017-33842] awarded by the Spanish

Ministry of Economy and Competitiveness. KNI and JMP acknowledge funding from the Scottish Government's Rural Affairs, Food and Environment Strategic Research Portfolio. IM is supported by the TEAM-NET programme of the Foundation for Polish Science, co-financed by the European Regional Development Fund under the Smart Growth Operational Programme [grant number POIR.04.04.00-1763/18-00]. NK acknowledges funding by the German Federal Ministry of Education and Research (BMBF) [grant number 01LN1705A]. RM is supported from the BMBF [grant number 01KI1717] as part of the National Research Network on Zoonotic Infectious Diseases of Germany, and from the BiodivERsA3 ERA-Net COFUND programme (2018-2019 BiodivERsA joint call for research proposals) [grant number G0G2319N]. SL and PC are supported by the UK Natural Environment Research Council, the Arts and Humanities Research Council and the Economic and Social Research Council under the Valuing Nature Programme [grant number NE/N013530/1].

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