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Invited Review

Biodiversity and human health: mechanisms and evidence of the positive health effects of diversity in nature and green spaces

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Abstract

Introduction: Natural environments and green spaces provide ecosystem services that enhance human health and well-being. They improve mental health, mitigate allergies and reduce all-cause, respiratory, cardiovascular and cancer mortality. The presence, accessibility, proximity and greenness of green spaces determine the magnitude of their positive health effects, but the role of biodiversity (including species and ecosystem diversity) within green spaces remains underexplored. This review describes mechanisms and evidence of effects of biodiversity in nature and green spaces on human health.

Sources of data: We identified studies listed in PubMed and Web of Science using combinations of keywords including ‘biodiversity’, ‘diversity’, ‘species richness’, ‘human health’, ‘mental health’ and ‘well-being’ with no restrictions on the year of publication. Papers were considered for detailed evaluation if they were written in English and reported data on levels of biodiversity and health outcomes.

Areas of agreement: There is evidence for positive associations between species diversity and well-being (psychological and physical) and between ecosystem diversity and immune system regulation.

Areas of concern: There is a very limited number of studies that relate measured biodiversity to human health. There is more evidence for self-reported psychological well-being than for well-defined clinical outcomes. High species diversity has been associated with both reduced and increased vector-borne disease risk.

Growing points: Biodiversity supports ecosystem services mitigating heat, noise and air pollution, which all mediate the positive health effects of green spaces, but direct and long-term health outcomes of species diversity have been insufficiently studied so far.

Areas timely for research: Additional research and newly developed methods are needed to quantify short- and long-term health effects of exposure to perceived and objectively measured species diversity, including health effects of nature-based solutions and exposure to microbiota.

Key words: biological diversity, ecosystem services, mental health, physical health, well-being

Introduction

Natural environments and frequent contact with nature have beneficial effects on human health and well-being.[1–5] The physical and mental health benefits associated to the interaction with natural and man-made green environments depend, in the first place, on the duration and timing of the exposure.[6–8] Short-term exposure to forests, urban parks, gardens and other (semi-) natural environments reduces stress and depressive symptoms, restores attention fatigue, increases self-reported positive emotions and improves self-esteem, mood, and perceived mental and physical health.[9–14] Access to natural environments also tends to enhance outdoor physical activity, hereby improving physical health, for instance, by reducing prevalence of obesity and type 2 diabetes.[15–20] Long-term exposure to natural environments, such as residing in areas with high greenness or in diverse landscapes, has been associated to reduced all-cause, respiratory, cardiovascular and cancer mortality[4,21] and to improved respiratory and mental health.[22,23] The effects of 'chronic' exposure to green spaces have been investigated over varying spatial scales, and positive effects of green spaces have been demonstrated over distances varying between 150 m and 5 km.[23–27]

Exposure to green or natural environments is particularly important during prenatal development and early life. The greenness of mother's neighbourhoods has a positive effect on the birth weight of their infants.[4,28,29] Childhood exposure to natural environments reduces the risk of developing schizophrenia.[30] Residential greenness has been associated to reductions in obesity prevalence and atopic sensitization in children[16,31] and has a positive effect on blood pressure in adolescents.[32] Early life exposure to natural environments also has a number of important long-term effects. The exposure to beneficial microbiota in the environment during the early life has profound effects on the development of the immune system and on the prevalence of chronic inflammatory diseases.[33–37] In addition, early exposure to nature amplifies the potential beneficial effects of green spaces in later life,[38] including the stress-reducing effects of therapeutic immersion in nature.[39,40] Conversely, the lack of interaction with nature during early life, for instance, due to the limited time spent in nature or green space in urbanized environments, has been associated to a number of emotional, cognitive and physical difficulties in children. The set of mental disorders linked to this disconnection with nature has been described as 'nature deficit disorder' (NDD).[41]

The short- and long-term benefits that natural and man-made green spaces provide, in terms of human health, can be classified as 'ecosystem services'.[42–46] Ecosystem services are 'the ecological characteristics, functions or processes that directly or indirectly contribute to human well-being, i.e. the benefits people derive from functioning ecosystems'.[47] Environments provide food, fuel, fresh water, medicines and other materials ('provisioning services'); regulate local and global climate, air quality, pollination, pests and vector-borne diseases ('regulating services'); provide habitat for biological diversity and maintain genetic diversity ('supporting services') and offer space for spiritual, recreational and intellectual interaction with natural environments ('cultural services').[48] A growing body of evidence shows that many observed associations between exposure to green environments and human health and well-being benefits are mediated by a number of crucial ecosystem services.[49] These include cultural ecosystem services that have an impact on stress and regulating ecosystem services that reduce harmful environmental exposure such as air pollution, extreme heat, urban heat and noise.[4,50–52]

Earlier review work on biodiversity and human health focused mainly on the effects of presence, availability, size, accessibility, proximity or greenness of various (urban) green spaces.[12,19,31,34,53] The role of actual biodiversity within green spaces remains highly underexplored. Biodiversity not only encompasses the variety of species (animals, plants, fungi and microorganisms) but also the variety of genes within those species and the variety of ecosystems in which the species reside.[54] Yet, there are apparently evident cascading links between green environments, biodiversity, ecosystem services and human health and well-being (Fig. 1).[55–62] For example, high plant diversity may result in high structural and functional variation which determine the potential of green spaces to mitigate air pollution.[63] Also, biodiverse green spaces may host a high diversity of environmental microbiota,[64] which may mediate biodiversity effects on human health through their impact on the immune system.[33–37] Thus, plant diversity may have direct and indirect impacts on the potential of green spaces to reduce the acute and chronic health effects of air pollution, including allergies, asthma, cardiovascular diseases and premature death (Fig. 2).[65–68]

Accumulating evidence shows that ecosystems with a high level of biodiversity are more likely to be more efficient in providing high levels of multiple ecosystem services ('biodiversity–ecosystem functioning theory'). Diverse systems have also been shown to be more resilient in the face of natural and anthropogenic disturbances ('ecological resilience theory'),[69,70] which is important in urban settings. Here, we review the evidence for effects of actual biodiversity for the three main mechanisms that link biodiversity in nature and green spaces to human health and well-being: the 'biophilia hypothesis', the 'biodiversity hypothesis' and the 'dilution effect hypothesis'.

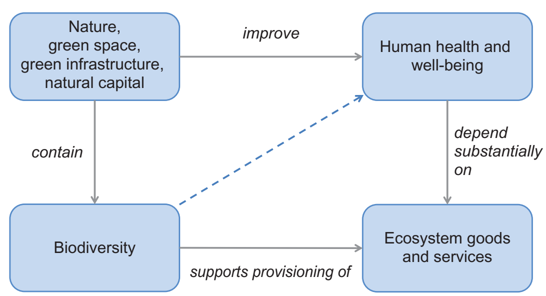

Fig. 1 Linkages between nature, biodiversity, ecosystem services, and human health and well-being.

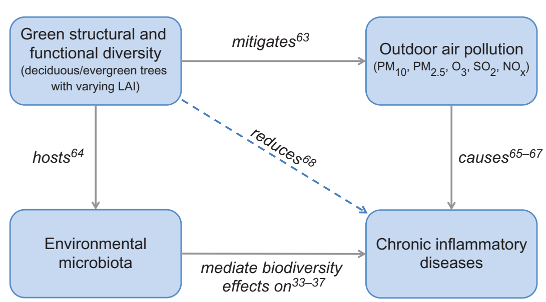

Fig. 2 Direct and indirect effects of biological diversity on human health: example for the mitigation of air pollution.

The 'biophilia hypothesis' proposes that humans have an intrinsic affinity to other species and nature because the interaction with the natural environment drove the evolution of our species.[71] Under the biophilia hypothesis, people are expected to prefer and select biologically diverse environments and derive mental benefits from exposure to green space.[3,72–74] Biophilia studies are often framed in 'stress 'recovery theory' (natural environments facilitate the recovery from physiological stress)[75] and 'attention restoration theory' (natural environments facilitate the recovery from mental fatigue and assist the restoration of directed attention).[76]

The 'biodiversity hypothesis' proposes that exposure to biodiversity improves the immune system by regulating the species composition of the human microbiome.[77,78] Under this hypothesis, exposure to beneficial environmental microbiota reduces the prevalence of allergies, asthma and other chronic inflammatory diseases.[33–35,37,78,79] The related 'hygiene hypothesis' and 'microflora hypothesis' state that a reduced early life exposure to parasites and environmental bacteria is associated with an increased risk to develop allergic diseases, asthma and other hypersensitivity disorders because it has detrimental effects on the development of the human (intestinal) microbiome (dysbiosis) and the infant immune system[80–82] (for a review on the health effects of commensal microbiota and parasitic helminths, which are beyond the scope of this review, see e.g. the work done by Stiemsma *et al.*).[83]

The 'dilution effect hypothesis' proposes that high vertebrate species richness reduces the risk of infectious diseases of humans because pathogens are 'diluted' among a high number of animal reservoir species that differ in their capacity to infect invertebrate vector species.[84] Under the dilution effect hypothesis, transmission and burden of infectious diseases are expected to be lower in animal species-rich natural environments because the prevalence of infected vectors is lower,[85–90] despite expected higher pathogen richness[91] and elevated risks of pathogen spillover from those various hosts to humans.

Much of the earlier work on the effects of environmental biodiversity on human health has focused on Lyme disease (borreliosis), a tick-borne infectious disease caused by bacteria of the *Borrelia* genus. Syntheses of the available evidence reported in the literature on the complex ecology of Lyme disease have yielded opposing conclusions: some authors conclude that biodiversity strongly reduces human risk of Lyme disease[92] and others suggest that Lyme disease risk increases with biodiversity.[93] As a result, the relationship between biodiversity and human risk of Lyme disease remains fiercely debated.[94–98] Here, we look for evidence of biodiversity effects on human health beyond Lyme disease. We focused our review on the question whether biodiverse green environments are more beneficial for promoting human health than less biodiverse green environments.

Methods

Search strategy

Between October 2017 and May 2018, electronic searches were conducted in the Web of Science database using queries that targeted papers on nature and green spaces (set 1: 'forest', 'garden', 'green space', 'nature', 'park', 'green environment' or 'natural environment'); biodiversity (set 2: 'biodivers*', 'divers*' or 'species richness'); human health (set 3: 'human health', 'mental health', 'well-being', 'physical health' or 'psychological health') and specific health outcomes (set 4: 'cancer', 'COPD', 'allerg*', 'obesi*', 'diabet*', 'pulmon* disease', 'respiratory disease', 'cardio* disease', 'mental disease', 'mortality' or 'morbidity'). We then combined sets to find papers on nature, biodiversity and health (set 5) and nature, biodiversity and specific health outcomes (set 6) (Supplementary material, Table S1). Additional electronic searches were conducted in the PubMed and Cochrane databases using the isolated or combined keywords 'biodiversity', 'diversity', 'species richness', 'human health' and 'well-being' (e.g. 'species richness' AND 'human health') with no restrictions on the year of publication. The citing articles and cited references features in Web of Science and from Crossref's cited-by linking service and Google Scholar and journal TOC alerts were used to identify additional articles that were not returned by the initial electronic searches, for instance because they were not yet indexed or were under review or in press at the time of our initial study. The title and abstract of each potentially relevant article were screened. Papers were considered for detailed evaluation if they were written in English and if they reported data on levels of biodiversity and on physical or psychological health outcomes. For all studies included in the review, full-text versions, and if necessary, online supplementary material, were obtained to extract data.

Search results, data extraction and study population

The initial electronic search identified 7354 studies as potentially relevant (Supplementary material, Table S1). The vast majority of these studies were excluded after screening title and abstract because they were not relevant (i.e. studies that contained our keyword combinations but in contexts outside the scope of our study). A large number of studies and reviews only reported qualitative 'biodiversity' data (i.e. presence, availability, size, accessibility, proximity or greenness (NDVI) of various green space types, often in contrast with 'gray' spaces). These studies were discussed in the introduction of this paper but excluded from the systematic review. Nineteen studies that reported biodiversity information and health outcomes published between 2006 and 2018 met the inclusion criteria.

For each included study (n = 19), the following information was extracted from the full text and online supplementary material: environment and location of the study, indicator(s) of biodiversity, human health outcome(s) and the associations between biodiversity and human health. Information on size (N), male/female ratio and age structure of the human study population were also extracted when provided in the text or supplementary material.

Eleven studies reported population size. The total number of study subjects across these 11 studies was 45 172 (range 112–39 108; median 569, interquartile range 957).

Evidence for biodiversity effects on human health

Areas of agreement

Ten studies provided evidence in support of the biophilia hypothesis, three studies evaluated the biodiversity hypothesis and six studies evaluated the dilution effect hypothesis (Table 1). Self-reported psychological well-being was by far the most studied human health aspect (8 out of 10 studies, 80%). Two studies reported biodiversity effects on self-reported physical and general health.[102,104] One study explored the relationship between biodiversity and physiological parameters (heart rate, blood volume pulse and facial muscle tension).[105] Most studies were performed in urban environments (urban green spaces, urban residential neighbourhoods, parks and gardens; n = 7). Geographically, most evidence was recorded in Great Britain (n = 7) and the USA (n = 3); the other studies took place in Italy, Germany, Finland, New Zealand, Australia and Taiwan. Three studies were meta-analyses or were performed at continental (13 Latin American countries) or global scale (60 countries).

Across the 19 studies, 40 associations between biodiversity indicators and human health were evaluated: 24 associations were significantly positive (60%), three associations were significantly negative (8%) and 13 associations were not statistically significant (33%) (Table 2). Most evidence for positive effects of biodiversity on human well-being was found for measured and perceived bird species richness (10 positive associations in 13 tests; 77%), followed by plant species richness (5 positive associations in 10 tests; 50%), habitat diversity (4 positive associations in 5 tests; 80%) and perceived butterfly richness (2 positive associations in 3 tests; 66%) (Table 2).

The many observed positive associations between bird species richness and well-being may stem from a study bias: birds are relatively easy to observe, are important providers of ecosystem services[116] and are suitable indicators of biodiversity in agricultural mosaics and patchy landscapes.[117] Whether birds directly generate human health benefits or merely

Table 1 Studies providing evidence for the association between human health and biological diversity in nature and green spaces

Study	*N*, M/F	Age (*y*)	Environment	Diversity indicator	Human health aspect	Association
Biophilia hypothesis						
Fuller *et al.*[99]	312	16–70+	Urban greenspaces, UK	Second-order jackknife estimator of total plant species richness; number of butterfly and bird species; perceived species richness of plants, butterflies and birds; number of habitats	Self-reported psychological well-being (cognitive restoration, positive emotional bonds and sense of identity)	Well-being measures were positively associated with plant richness (reflection and identity), bird richness (continuity with past and attachment) and number of habitat types (reflection, identity, continuity with past)
Luck *et al.*[100]	1078		Urban residential neighbourhoods, Victoria and New South Wales, SE Australia	Native bird species richness and abundance, vegetation cover and density	Self-reported personal well-being (Personal Wellbeing Index fourth edition)	Personal well-being was positively associated with bird species richness and abundance and vegetation cover and density
Dallimer *et al.*[101]	1108, 687/421	16–70+	Riparian greenspaces, UK	Bird, butterfly and plant species richness; perceived species richness of plants, birds and butterflies, habitat diversity	Self-reported psychological well-being (reflection, attachment and continuity with the past)	Psychological well-being was positively associated with perceived richness (birds, butterflies, plants) and actual bird richness but negatively associated to actual plant diversity
Carrus *et al.*[102]	569, 274/295	M 41 SD 17.9	Urban and peri-urban green spaces, Italy	Ordinal biodiversity levels (low diversity: urban squares with green elements, peri-urban pinewood forest plantations; high biodiversity: urban parks, peri-urban natural protected areas)	Self-reported psychological well-being (Perceived Restorativeness Scale) and self-reported physical well-being	Self-reported psychological (subjective) well-being was positively associated with biodiversity
Cox and Gaston[103]	331, 146/185			Species richness and abundance of common	Self-reported pleasure, connectedness to nature	Pleasure and well-being benefits of birdwatching

Continued

Table 1 *Continued*

Study	*N*, M/F	Age (*y*)	Environment	Diversity indicator	Human health aspect	Association
			Gardens, Milton Keynes, Luton and Bedford, England, UK	garden birds (choice experiment)		increased with diversity of birds and knowledge of species
Wheeler *et al.*[104]			All land covers, England, Wales and Scotland, UK	Shannon land cover diversity; bird species richness	Self-reported general health (2011 UK census)	Good health prevalence was positively associated to land cover diversity and bird species richness
Chang *et al.*[105]	151, 80/71	18–45+	Mixed-use urban green space, suburban and rural mixed landscape of farmland and natural vegetation, and mountain forest, Taiwan	Species richness, abundance, diversity and evenness of insects	Heart rate, blood volume pulse and facial muscle tension were used as indicators of physiological well-being	Physiological responses of wellness did not increase with insect biodiversity
Marselle *et al.*[106]	127, 57/70	55–74	England, UK	Perceived bird, butterfly and plant (tree) biodiversity	Pre- and post-walk self-reported emotional well-being (positive effect, happiness, negative effect)	Perceived restorativeness was positively correlated to perceived bird, butterfly and plant/tree species richness and to post-walk positive effect and happiness
Cox *et al.* (2017b)[107]	263	31–60+	Urban environment, Milton Keynes, Luton and Bedford, England, UK	Neighbourhood vegetation cover, actual bird species richness and abundance, afternoon bird species richness and abundance	Self-reported depression, stress and anxiety (Depression, Anxiety, and Stress Scale, DASS 21)	High levels of vegetation cover and high afternoon bird abundance (but not richness) were associated to lower depression, anxiety and stress
Hoyle *et al.*[108]	1411, 524/874	18–65+	Parks and gardens in England, UK	Perceived biodiversity (plant species, native plant species, insects, native insects)	Self-reported restorative effects	Restorative effect was correlated to perceived shrub plant species richness (but not to

Continued

Table 1 *Continued*

Study	*N*, M/F	Age (*y*)	Environment	Diversity indicator	Human health aspect	Association
						perceived herbaceous or woody species richness); perceived biodiversity was correlated to perceived attractiveness and perceived attractiveness was weakly correlated to restorative effect
Biodiversity hypothesis						
Ege *et al.*[109]	933	6–13	Family-run farms and controls, Bavaria, South Germany	Molecular marker of exposure to bacteria in environmental dust; number and diversity of bacterial and fungal colonies grown from airborne dust	Asthma (incl. multiple diagnoses of wheezy bronchitis) and atopy (presence of IgE antibodies to dust mites, cat antigen, tree mix or birch, or a positive reaction to grass mix)	Prevalences of asthma and atopy were significantly lower in children on farms compared to reference group; microbial diversity and specific microbial exposure were protective factors against asthma and atopy (OR $<$ 1)
Hanski *et al.*[78]	112, 46/66	14–18	Eastern Finland	Environmental biodiversity (forested and agricultural land within 3 km of the home); species richness of plant groups in yards; skin microbial diversity	Atopy, based on skin prick testing and IgE antibody levels	Atopy decreased with increasing environmental biodiversity and species richness of (uncommon native) flowering plants (but not with other plant groups); atopic individuals had lower diversity of gammaproteobacteria on the skin
Donovan *et al.*[110]	39 108	<0–18	New Zealand	Number of natural land cover types in residential area	Childhood asthma	A higher number of natural land cover types was associated with a lower risk for childhood asthma

Continued

Table 1 *Continued*

Study	*N*, M/F	Age (*y*)	Environment	Diversity indicator	Human health aspect	Association
Dilution effect hypothesis						
Ezenwa *et al.*[111]			Various land covers, Louisiana, USA	Passerine and non-passerine bird species richness	West Nile virus (WNV) infection rates in mosquitoes and humans	Non-passerine bird diversity was negatively correlated with WNV infection rates in mosquitoes and humans
Swaddle & Calos[112]			Various land covers, eastern USA	Avian (viral reservoir host) diversity	Incidence of human WNV infection	Incidence of WNV was lower in counties that had greater avian diversity
Civitello *et al.*[88]			Meta-analysis of published studies	Diversity of hosts (most often reported as species richness)	Human parasite abundance	Negative effect size indicated strong negative relationship between host diversity and human parasite abundance
Hamrick *et al.*[113]	1164 cases		Argentina, Bolivia, Brazil, Colombia, Ecuador, French Guiana, Guyana, Panama, Paraguay, Peru, Suriname, Trinidad and Tobago, and Venezuela	Diversity of non-human primate (NHP) hosts (number of different genera of NHP hosts)	Presence of yellow fever (YF) by county (confirmed YF cases)	YF presence was associated to NHP host diversity (OR 1.8)
Levine *et al.*[114]			Mixed-use parks, residential areas and old-growth forest in urban Atlanta, Georgia, USA	Avian host diversity (Shannon–Wiener diversity index *H'*)	Host WNV seroprevalence and vector infection rates	Increased host diversity was associated to increased WNV seroprevalence and infection rates (amplification effect)
Wood *et al.*[115]			Various systems, global (60 countries)	Integrated bird and mammal species richness estimate based on grid-based biodiversity data and forest cover	DALYs per 100 000 people for 24 infectious diseases	Increases in biodiversity over time not correlated with improvements in human health

serve as indicators of overall landscape biodiversity having an impact on human health remains unclear. However, most studies included in this review did not use bird species richness in isolation but included other components of biodiversity in their analyses, including habitat diversity and plant and butterfly species richness. These studies often found positive effects of birds but not for one or more other indicators (e.g. effects of bird and plant species richness but not of butterfly richness;[99] effects of perceived bird diversity but not of perceived butterfly or plant diversity[106]). In another study, Cox and Gaston[103] demonstrated that the pleasure of birdwatching and the associated well-being benefits of interaction with birds increased with the knowledge of the names of the species. Across participants, in particular songbirds were highly appreciated. Elsewhere, Cox *et al.*[107] showed that the richness of the birds people are most likely to see (a high afternoon bird abundance) and not the true total species richness of birds reduced depression, anxiety and stress. It is therefore plausible that the observed positive effects of birds on mental well-being[99–101,104] are true effects of birds *per se*. These results illustrate that visual and non-visual stimuli, such as bird vocalizations, and other psychological pathways may significantly contribute to the positive effects of nature on mental health and stress levels.[118] Equally important, these results also demonstrate that the benefits of interaction with nature may be highly dependent on individual characteristics and preferences and are therefore expected to vary significantly across the general population.

Two studies on adolescents and the microbial diversity in their environment provided strong evidence for the biodiversity hypothesis and offer a different mechanistic explanation for the positive effects of biodiversity on human health. Using two cross-sectional studies, Ege *et al.*[109] compared children (6–13 years old) living on family-run farms to children in a reference group in Bavaria (South Germany). The prevalence of asthma and atopy (based on the presence of IgE antibodies to dust mites, cat antigen, tree pollen mix or birch, or a positive reaction to grass pollen mix) were significantly lower in children on farms compared to the reference group. Microbial diversity was assessed in indoor dust obtained from mattresses and children's rooms. Microbial diversity and specific microbial exposure (exposure to *Eurotium* fungi and to bacteria including *Listeria*, *Bacillus* and *Corynebacterium* species) were protective factors against asthma and atopy (odds ratios (ORs) ranging between 0.37 and 0.86 and all 95% confidence interval upper limits <1). Hanski *et al.*[78] determined atopy (based on skin prick tests and IgE antibody levels) in school children (14–18 years old) in eastern Finland. Atopy decreased with increasing environmental biodiversity (calculated as the amount of forest and agricultural land within 3 km of the home) and with species richness of uncommon native flowering plants (but not with other plant groups). Atopic individuals had a lower generic diversity of gammaproteobacteria on their skin. A third study also supported the biodiversity hypothesis, although no direct link to microbial diversity was made. In a large birth cohort study in New Zealand,[110] the number of natural land cover types in the neighbourhood of a child's residence was associated to a lower risk for childhood asthma. These results have also been confirmed in a cohort study of Finnish and Russian children, in which differences in allergy patterns between populations during the 10-year follow-up period were paralleled by differences in skin and nasal microbiota.[35] Results from these studies support the biodiversity hypothesis: microbiota are very likely to mediate the effects of biodiversity on human health, by regulating the immune system and protecting against allergy and asthma.[80,82]

Areas of concern

For some taxa such as plants and butterflies, positive effects of 'perceived' biodiversity on well-being were not confirmed by positive effects of 'measured' biodiversity of these taxa. The results for measured plant species richness, for instance, were equivocal: Fuller *et al.*[99] recorded a positive association between estimated total plant species richness in urban green spaces and self-reported well-being, whereas Dallimer *et al.*[101] reported a negative association between plant diversity and self-reported psychological well-being in a larger study in riparian green spaces. Despite

Table 2 Associations between biodiversity indicators and human health observed in 19 published studies

	Plants	Butterflies	Birds	Insects	Microbiota	Mammals	Habitats	Overall
Measured	++[78,99] N[78] –[101]	NN[99,101]	+++++++[99,100,101,104,107,111,112] N[107] –[114]	N[105]	+[109]	–[113]	++++[78,99,104,110] N[101]	+[88] N[115]
Perceived	+++[101,106,108] NNN[99,108,108]	++[101,106] N[99]	+++[101,103,106] N[99]					+[102] N[102]
$\sum +$	5/10 (50%)	2/5 (40%)	10/13 (77%)	0/1 (0%)	1/1 (100%)	0/1 (0%)	4/5 (80%)	2/4 (50%)

+, significant positive association; N, no significant association; –, significant negative association.

concerns over potential health impacts of 'invasive alien species',[119] such as increased allergy prevalence caused by the spread of invasive ragweed,[120] only one study on human health impacts of biodiversity included health impacts of invasive alien species—in the New Zealand birth cohort study, which associated land cover diversity to lower childhood asthma risk, two non-native, low-biodiversity land cover types were associated to an increased risk for asthma.[110] Also, studies focused mainly on 'self-reported psychological well-being' and not on well-defined clinical outcomes. Moreover, associations between biodiversity and health may be mediated and modified by numerous underlying perceptions and properties of the subjects such as perceived intensity of the exposure, cultural background or income.[104,106] These results suggest that the observed effects of biodiversity on mental well-being and general health are subjective and that different definitions or methods for quantifying well-being, general health and perceived biodiversity may have strong impacts on the results.[100,101]

The effect of biodiversity on 'risk and burden of vector-borne diseases' is a major area of concern. Studies that focused on the effect of biodiversity on the transmission of a single pathogen, such as West Nile virus (WNV), found evidence in support of the dilution effect hypothesis. Ezenwa *et al.*[111] showed that WNV infection rates in mosquitos and humans were negatively correlated with non-passerine bird diversity in various land use types in Louisiana, USA, suggesting that wild bird diversity contributes to minimizing human WNV disease risk. In a geospatial study across eastern US counties, Swaddle and Calos[112] observed a similar dilution effect: the incidence of WNV was lower in counties that had a greater diversity of birds, the principal reservoir hosts of WNV. In a meta-analysis of 202 effect sizes on 61 parasite species, Civitello *et al.*[88] presented 'broad evidence' in favour of the dilution effect hypothesis, showing that host diversity (most often reported as species richness) 'inhibits parasite abundance'.

More recently, however, evidence for an opposite effect have emerged: the 'amplification effect' or positive association between host diversity and prevalence and infection rates of infectious agents. Across the

Americas, the presence of yellow fever (YF) by county (1164 confirmed YF cases) was significantly positively associated to the diversity of non-human primate (NHP) hosts (determined as the number of NHP genera) (OR 1.8).[113] In mixed-use parks, residential areas and old-growth forest in urban Atlanta, Georgia, USA, Levine *et al.*[114] demonstrated that WNV seroprevalence and infection rates increased with increasing avian host diversity, contradicting the results of Swaddle and Calos.[112] Recent insights have demonstrated that earlier reports in support of the dilution effect hypothesis may have been flawed by focussing on single or too narrow sets of pathogens such as *Borrellia*. In a global study across 60 intermediate-sized countries, Wood *et al.*[115] investigated spatial and temporal relationships between per-person disability-adjusted life years (DALYs) lost to infectious disease and potential drivers including biodiversity. The authors estimated satellite-derived forest cover and integrated bird and mammal species richness using published grid-based biodiversity data and calculated DALYs per 100 000 persons for 24 infectious diseases in 2010 (in terms of DALYs, the most important diseases were HIV/AIDS, malaria, tuberculosis and typhoid). For only two diseases, biodiversity appeared to be a significant driver of disease burden. The effect was positive for one group of diseases (food-borne trematodiases, caused by parasitic flatworms) and negative for the other (lymphatic filariasis or elephantiasis, caused by nematodes). Conversely, the study found that forest expansion (which may be a proxy of increasing biodiversity) is associated with higher burdens of infectious disease. Thus, at present, the hypothesis that high biodiversity protects the human population from infectious diseases by diluting pathogens in unsuitable host species remains under discussion.

Areas timely for research

Novel methods are needed to accurately quantify environmental exposure, i.e. exposure to potential harmful emissions (e.g. air pollution) or environmental conditions (e.g. urban heat) as well as exposure to different dimensions of biodiversity (e.g. allergenic pollen).[121] 'Mobile health applications' in smartphones that use GPS technology and internet connectivity can be used to precisely track whereabouts of persons while simultaneously collecting personal data (such as activity, heart rate and stress), environmental data (such as air quality, temperature, air humidity and even radiation) and medical data (such as acute allergic symptoms).[122] At the same time, recent advances in high-resolution hyperspectral imaging technology have enabled the fine-scale functional characterization of vegetation and the spatio-temporal mapping of biodiversity.[123] Combining these emerging technologies will enable health and environment scientists to precisely quantify exposure doses and help to elucidate the complex interactions between human health, biodiversity, environmental pollutants and a multitude of confounding factors such as living environment and lifestyle.[34,124]

More research is needed to assess the health impact of emerging nature-based solutions. Among others, the following interventions merit special attention:

Urban blue infrastructure—blue landscape elements in cities contribute to improved urban water cycles and generate a number of health benefits related to the regulation of the urban climate. More research is needed on the potential impacts of blue infrastructure on vector-borne diseases.[125]

City trees—city trees have potential impacts on air quality (both positive and negative)[126] and temperature and may have implications for the prevalence and severity of respiratory and cardiovascular diseases. Urban trees can also be sources of allegenic pollen and the allergenicity of tree species must be considered in urban green planning.[125,127]

Green school playgrounds—school playgrounds equipped with green infrastructure may increase early life exposure to beneficial urban soil microbiota and reduce the incidence of NDD.[73,128]

Wildlife provisioning—increasing wildlife populations in the vicinity of people by providing resources for wildlife, such as bird feeding stations, may stimulate human-nature interactions and generate indirect health benefits.[129,130]

Forest bathing—'Shinrin-yoku' (therapeutic forest walks) and other nature-based therapies are increasingly popular but lack scientific validation so far.[39,131]

Finally, most studies on biodiversity and human health have focussed on the short-term effects of exposure to biodiversity and often lack proper experimental design. Further research on short-term exposure effects should preferentially adopt randomized controlled trial designs. In addition, few studies acknowledge that the effects of exposure do not necessarily overlap with the timing of exposure. Therefore, additional studies need to take into account the various time lags that could occur in nature dose–health response relationships.[124] Longitudinal studies, such as birth cohort studies,[36,110,132] rather than cross-sectional studies, seem to be most appropriate to validate the long-term benefits of biodiversity on human health.

Conclusion

It is well established that loss of species from an ecosystem may ultimately decrease its ability to provide ecosystem services.[133,134] Some of these ecosystem services relate to mitigating heat, noise and air pollution, which mediate human health and well-being.[124,135,136] Therefore, there is a need for the conservation and restoration of biodiversity.[137–139] However, whereas positive effects of green spaces and nature contact on mental and physical health are well documented,[19,124,140] there is rather limited evidence for direct biodiversity effects and conflicting evindence in terms of infectious diseases.[141] Novel methods are needed to accurately quantify the quantity and quality of exposure to different dimensions of biodiversity, including microbial diversity.[79,142] Epidemiological studies, complemented by studies in animal models,[83,143,144] are needed to assess the effects of combined environmental exposures (to biodiversity, to pollution, to microbiota, etc.) on quantitative health outcomes. Such novel exposure and response assessments are essential to guide biodiversity-based therapy and to inform environmental policies that aim to maintain and develop nature beneficial to human health inside and outside urban areas, such as nature-based solutions and green infrastructure.[64]

Supplementary material

Supplementary material is available at *British Medical Bulletin* online.

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Conflicts of interest statement

The authors have no potential conflicts of interest.

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