

Links between biodiversity and human infectious and non-communicable diseases: a review

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Summary

INTRODUCTION: Biodiversity has intrinsic value and a fundamental role in human health. The relationship between them is complex, and the specific sustaining processes are still not well understood. In view of the rapidly evolving landscape, this literature review investigated scientific evidence for specific links between biodiversity and human infectious and non-communicable diseases to characterise identifiable relationships.

METHODS: A search of the PubMed and Web of Science databases using keyword algorithms identified relevant manuscripts published between 1 January 2000 and 18 April 2019. Qualitative data were extracted from 155 studies investigating links between or mechanisms linking biodiversity and infectious disease, non-communicable disease, allergic/inflammatory disease and microbiomes.

RESULTS: None of the reviewed studies documented causal evidence for a mechanism linking biodiversity and human health. The main mechanisms proposed to link biodiversity and transmission of infectious disease were dilution and amplification. The dilution hypothesis argues that an increase in species diversity leads to a decrease in pathogen prevalence. The amplification effect is the converse, that there is a positive correlation between species diversity and disease risk/infection prevalence. Several driving factors are postulated, including encounter reduction, interspecies competition and predation. In addition, it appears that scale, both spatial and temporal, highly impacts diversity-disease relationships. There is strong evidence that the early environment of a child, including maternally transferred prenatal signals, affects immune maturation, modifying later disease risk. Bi-directional axes communicate between the gut microbiome and the brain, as well as between the skin microbiome and the lung, leading to direct and indirect immune, humoral and neural mechanisms. The main challenges in assessing links between biodiversity and human health are the wide variation in definitions of health and biodiversity, and the heterogeneity in types of studies encountered, as well as the complexity of interactions in dynamic systems.

CONCLUSIONS: Contextually adapted integrative approaches, which maintain dialogue across disciplines and amongst all stakeholders, are most likely to generate robust evidence. Because of the relevance of local scale, research engagement must occur across levels to generate legitimate practices and translate into sustainable, equitable policies. Recommendations for future action include: improve the knowledge base on contribution of biodiversity to health, increase awareness of health effects of natural and near-natural environments and biodiversity, and promote synergies by increasing policy coherence.

Introduction

Biodiversity has intrinsic value and a fundamental role in sustainable development and human health. Biodiversity is necessary for proper ecosystem functioning and provision of ecosystem services, but it is not yet well-delineated which specific processes are primarily important in sustaining human health [1, 2]. Huynen et al. [3] described “health functions” provided by ecosystems, one of which could be summarised as “disease regulation”. Earlier discussions relating biodiversity to human health centred on provisioning services, with both scientific and public health communities advocating preservation of biodiversity as crucial for future human health [4]. This line of argument focused more on conservation than on biodiversity itself [5]. The Millenium Ecosystem Assessment broadly defined ecosystem services and considered links to many facets of human well-being [6]. Available tools in the fields of ecology and economy were applied to people-nature relationships, framing them as stock-and-flow processes, but social science and local practitioner perspectives were marginalised [7]. The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), a joint global effort by government, academia and civil society, further refined a conceptual framework, extending the idea of ecosystem services to encompass nature’s contributions to people [8]. In view of the rapidly evolving landscape, we investigated the current body of scientific evidence for specific links between biodiversity and human infectious and non-communicable disease, aiming to characterise identifiable relationships or

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mechanisms. Reliable evidence would be valuable for decision makers to adequately inform effective sustainable environmental and health related policies.

Definitions

Biodiversity: the variability among living organisms from all sources including, inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part: this includes diversity within species, between species and of ecosystems [9].

Ecosystem services: the benefits people obtain from ecosystems; four categories are distinguished – supporting services, provisioning services, regulating services and cultural services [6].

Health: a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity [10].

Nature's contribution to people: all the benefits that humanity – individuals, communities, societies, nations or humanity as a whole, in rural and urban settings – obtains from nature, encompassing ecosystem goods and services, which include provisioning, regulating and cultural services and nature's gifts [11].

Materials and methods

A search of the databases PubMed and Web of Science (WoS) on 16 April 2019 used key word algorithms to identify manuscripts related to biodiversity and health published from 2000 onwards. In PubMed, the search string was (biodiversity[Title/Abstract]) AND health[Title/Abstract] OR (biodiversity[Title/Abstract]) AND (disease*[Title/Abstract] OR transmission[Title/Abstract]), resulting in 2217 hits. In WoS, the search string was (TS=(biodiversity AND health) OR (biodiversity AND (disease* OR transmission) AND LANGUAGE: (English)), resulting in 6262 hits. EndNote™ bibliographic software was used to manage the citations. Duplicates were removed. Title and abstract review identified irrelevant studies. Inclusion criteria were studies investigating links between or mechanisms linking biodiversity and infectious disease, non-communicable disease, allergic/inflammatory disease and microbiomes. Exclusion criteria were irrelevant topic, based on title screening (e.g., land use, green space, medicinal plants, environmental/ecosystem services, invasive/introduced species, biodiversity conservation); health of non-human organisms; links connecting biodiversity and well-being / mental health, agricultural productivity, food security, human nutrition, health / air quality, health / noise mitigation, health / pharmaceutical development, health/water (fresh, ocean or wetland), and health/microclimates. Method studies (e.g., control efforts) and studies on the impact of climate change on biodiversity were excluded. Also excluded were studies with an abstract only, retracted studies and those in languages we were unable to translate (two Finnish, one Korean, one Chinese). The full text was reviewed for manuscripts fulfilling the inclusion criteria. Two additional studies were included following targeted review of included study bibliographies. The PRISMA flow diagram is depicted in [figure 1](#). Atlas.ti™ 7 software was used to extract data for qualitative coding from the selected articles.

Results and discussion

The 155 articles (see supplementary table S1 in the appendix) selected for this review focused specifically on biodiversity as it relates to human health in the context of infectious disease (92 papers) and non-communicable disease (36 papers). Twenty-seven manuscripts did not separate the two disease categories. Sixty-two papers were review articles, and the remainder were investigative studies, further categorised as observational (23), modeling (26), laboratory (3) or field (2) experimental, ecological (7) or not classifiable (32).

Infectious disease

We identified manuscripts on the topic of infectious disease, including both outbreaks and emergence of directly transmitted and vector-borne infections, relevant to biodiversity. Selected studies investigated the zoonoses bartonellosis [12], bovine tuberculosis [13, 14], echinococcosis [15], hantavirus [16–22], leptospirosis [23], Lyme disease [18–22] and West Nile virus [18, 21, 24–27], and vector-borne diseases Chaga's disease [28], malaria [18, 29, 30], schistosomiasis [12, 18, 31] and tick-borne encephalitis [32].

Mechanisms and drivers of infectious disease transmission

In 92 studies investigating links between biodiversity and infectious disease, two main mechanisms are proposed to influence transmission, dilution and amplification. The dilution hypothesis argues that an increase in species diversity leads to a decrease in pathogen prevalence. The assumption, at the local level, is that an increase in the number of non-host species decreases the number of intra-species encounters between infected and susceptible hosts, leading to a decrease in pathogen transmission rate and prevalence [33, 34]. Theoretical models, laboratory experiments, and observational and experimental field studies provide support to validate this hypothesis [35], but the generalisability of the concept is robustly debated [36–39]. The amplification effect is the converse of the dilution hypothesis, that there is a positive correlation between species diversity and disease risk / infection prevalence [13].

A number of drivers are postulated to influence these two different mechanisms. Several impact community structure and assemblage, including encounter reduction [13, 16], susceptible host regulation through interspecies competition or predation, which limits the abundance of competent hosts [13], and competition for food [12, 31]. All of these factors ultimately regulate host abundance and population density [40]. Community assemblage is complex, encompassing species richness (number of species), species evenness (relative abundance of the different species) and species composition (specific identities of species) [33]. It is suggested that species loss is not a random process. Species that are less able to adapt to changes in their environment could be more likely to disappear, whereas those that are resilient should increase to dominate local host communities [41], acting as vectors and pathogen reservoirs [42]. Host competence, the ability of a host to transmit disease, is an influential driver, which impacts patterns of transmission [12]. Biologists differentiate between low competence (alternative) hosts and decoy (completely un-

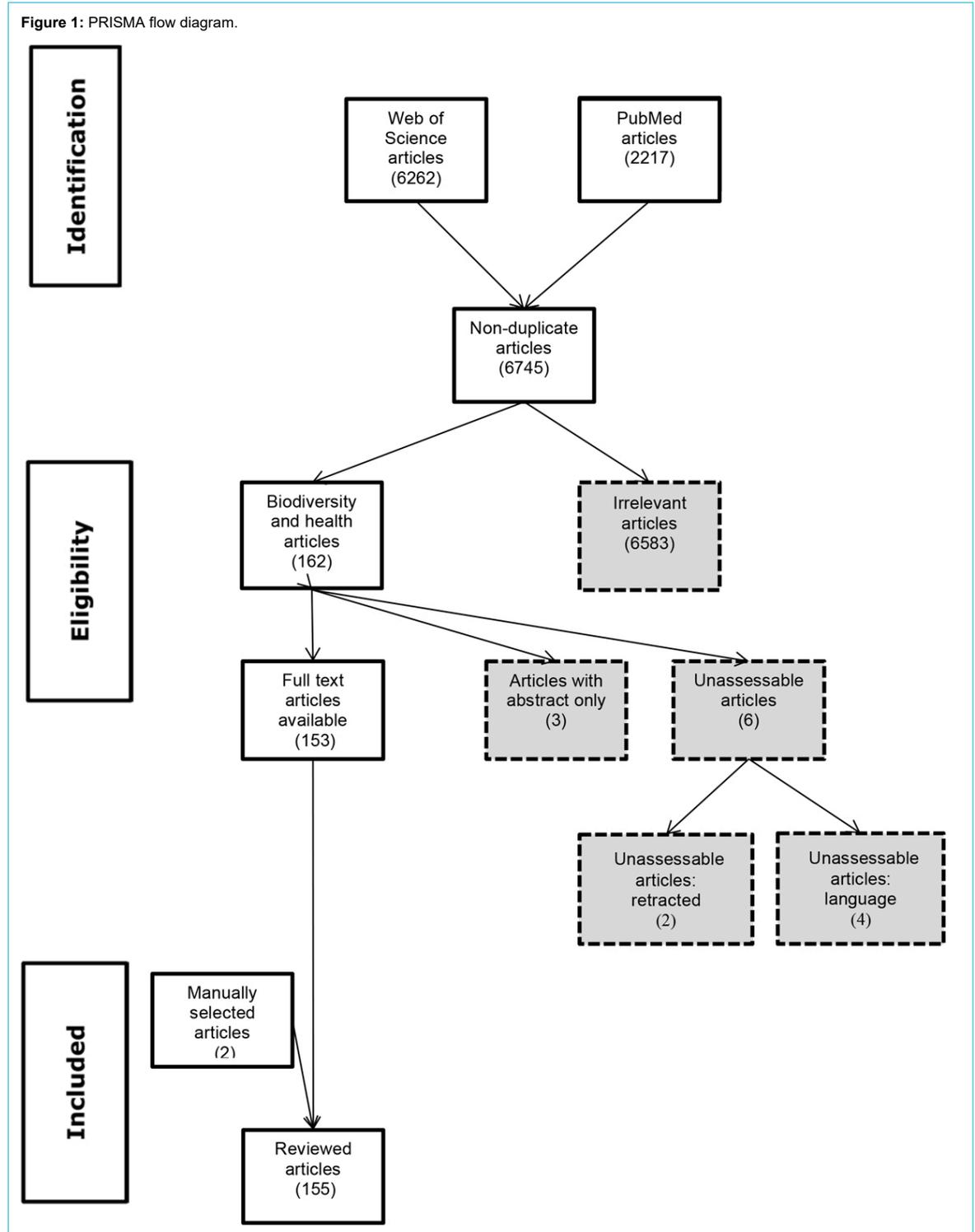
suitable) hosts, which result in wasted transmission opportunities [12, 21, 43].

Overlaying phenomena

The controversy about the postulated hypothesis of the relationship of health and biodiversity is also partially due to important overlaying phenomena that mutually affect each other and are difficult to disentangle [44, 45]. These are, among others, human and livestock population growth (particularly for chickens and pigs), habitat destruction and deforestation [46], (illegal) wildlife trade, low biosecurity and poor animal welfare in livestock production. The re-

cent spill-over and rapid spread of SARS-Cov2 into Danish captive mink [47], kept under extremely crowded and unsanitary conditions, could be considered as a negative example, thereby supporting the dilution hypothesis, but is clearly also related to intensive livestock production. The associated culling of 17 million mink in Denmark reflects animal mass killing and sheds an appalling light on current humane standards in animal production. Similarly, the so called “palm oil hypothesis” argues that the deforestation and planting of oil palms dislocated bats from their natural habitat and exposed oil palm plantation workers to the risk of Ebola spill-over, whereas the same populations would

Figure 1: PRISMA flow diagram.



have hardly been exposed to bats in a pristine rain forest in the same area [46].

Generalisability

It is widely agreed that scale has an outsized impact in the context of infectious disease. A recent review considered drivers of *Plasmodium knowlesi* transmission over multiple spatial scales from molecular to regional [29]. Identified factors influencing spread of disease were parasite-host evolutionary dynamics, diversity, abundance and range of host and vector species, and the spatial and temporal overlap between them. Untangling and understanding the causal mechanisms that generate diversity-disease relationships is only possible when collected data relate spatially and temporally to the relevant outcomes [27, 48–50], highlighting the importance of local scale. For instance, although species diversity may increase disease risk on a local scale (amplification), the mechanism of encounter reduction could operate at larger scales, resulting in an overall dilution effect [51]. Johnson and Thielges [12] illustrate the issue of divergence of spatial scale with two examples. Trematode miracidia are short lived and demonstrate significant spatial heterogeneity within a single wetland ecosystem, whereas tick vectors are comparatively long lived and travel on vertebrate hosts, vastly increasing their spatial scale of transmission. Habitat properties (land use, fragmentation) play an additional role in driving the mechanisms of dilution versus amplification [20], further supporting the argument for careful consideration of scale. Confounding becomes even more important when incidence data are collected from larger spatial scales than those in which transmission occurs [52], and often studies overlook spatial and temporal divergence [50].

Much of the research on the effect of biodiversity on infectious disease transmission has been on vector-borne diseases that are tick or mosquito transmitted. The inclusion of disease vectors makes transmission systems less tractable. This is because the dynamic interactions of (multiple) reservoir wildlife hosts, insect or arthropod vectors, livestock, companion animals and humans are highly complex and there are very few datasets that address their spatio-temporal dynamics in relation to biodiversity.

Directly transmitted diseases have received less attention, although they are easier to analyse from a mathematical perspective. We refer here to a recent study on Sin Nombre hantavirus modelled infection dynamics, using a multisite dataset to show that dilution and amplification occur at the same time in the same host-pathogen system [17]. There was an amplification effect, an increase in transmission rate, but overall net dilution, because the effect of diversity on the reservoir host population density was stronger. The authors conclude that how biodiversity affects individual mechanisms driving prevalence and their relative strengths must be considered in order to make generalisable predictions.

A closer look at the related mathematical approach allows a better understanding of the phenomena involved. The authors use a susceptible-infectious-recovered framework which conceptualises the drivers of the transmission, as depicted in equations 1 and 2 and figure 2, as frequency- and density-dependent processes.

Density-dependent transmission is thereby proportional to the contact rate c between susceptible (S) and infected (I) individuals and the probability of transmission (transmissibility) α . The transmission rate $\beta = c\alpha$ is considered as the product of the contact rate and the transmissibility of a pathogen. Frequency dependence is observed if the transmission depends on the frequency of infected among the total population $N = (S + I + R)$ as (I/N) . From these equations, we can infer the relationship of biodiversity and disease transmission in figure 3. Dilution will occur if the host population density decreases and if contact rates and/or transmissibility, which is also dependent on host susceptibility, are decreased. An amplification would occur if increased species diversity leads to an increase of host density, contact rates and/or transmissibility. In conclusion, the dilution effect is confirmed if the host density drives the transmission process over the transmissibility of the pathogen. It has an important spatial or contextual aspect, showing that smaller scale transmission dynamics can indicate an amplification effect if transmissibility dominates over host density. This example shows that biodiversity is clearly related to the transmission of infectious diseases, but that this relationship is complex and scaled. It has to be disentangled for every specific pathogen and ecosystem in relation to humans in relation to urban and agro-ecosystems.

Equations 1 and 2

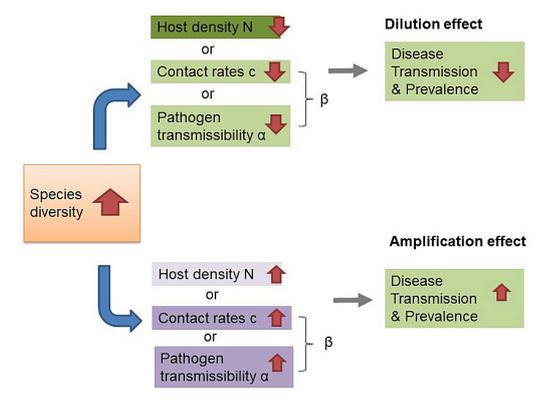
$$\frac{dI}{dt} = c\beta IS \quad (\text{Host density dependent transmission}) \quad (1)$$

$$\frac{dI}{dt} = c\beta IS / N \quad (\text{Host frequency dependent transmission}) \quad (2)$$

Figure 2: Flow chart of the transmission of an infectious disease in a given population.



Figure 3: Graphical depiction of how species diversity could affect transmission and prevalence of a directly transmitted disease (adapted from Luis et al. [17]).



Human exposure risk from infectious diseases of animal origin (zoonoses) can be estimated from animal-human transmission models. To our knowledge, very few such models exist and almost none address wildlife to human transmission. The so-called zoonotic potential of an infectious disease, the risk of transmission from animals to humans, can be estimated by the fraction of the transmission rates between animals β_a and between animals and humans β_{ah} as β_{ah}/β_a . For example the zoonotic potential of *Brucella melitensis* from small ruminants to humans in Mongolia is 1/15, whereas for *Brucella abortus* from cattle to humans it is 1/110. This shows that, in the same ecosystem, the risk of transmission of *B. melitensis* to humans is almost ten times higher than for *B. abortus* [53]. The risk of human rabies exposure from dogs in Chad in Central Africa is 1/400 [54] and the risk of transmission of bovine tuberculosis (*Mycobacterium bovis*) from cattle to humans is <1/1000 in Morocco [55]. These examples show how variable human exposure to directly transmitted zoonoses (stage 2) is and how dependent it is from a given agro-ecosystem. Wildlife reservoirs play a role in some of them [56, 57]. For example for *M. bovis*, the badger (*Meles meles*) is a reservoir host in the United Kingdom, which leads to continuous re-infection of cattle on pasture, and makes elimination of the disease almost impossible. Similarly, wild boar (*Sus scrofa*) and red deer (*Cervus elaphus*) carry *M. bovis* in some continental European countries. One could argue, as an example for the biodiversity-health link, that the introduction of large predators, such bears or wolves, could reduce red deer populations and hence reduce the risk of transmission of *M. bovis* to cattle, but this requires more research.

Non-communicable disease

We identified 36 manuscripts relevant to the effects of biodiversity on non-communicable diseases, within the broad grouping of allergic and inflammatory disease (including asthma), cardiovascular disease, and diabetes, and the relationship of microbiomes to health. Numerous studies suggest that microbe-rich environments are protective against inflammatory and autoimmune disease [58, 59], but recent work proposes that declining biodiversity more likely contributes to human immune dysfunction [60, 61]. The hygiene hypothesis proposes that modern lifestyles do not expose people to the microbial diversity (“old friends” or “keystone bacteria”) with which the human immune system evolved and which it requires for normal maturation [2, 62, 63]. This extends to the biodiversity hypothesis, that lack of exposure to natural environments and associated microbial diversity leads to dysbiosis in the human commensal microbiota, immune dysfunction and clinical disease [60, 64, 65]. Support for this hypothesis comes from work suggesting that the gut microbiome interacts with the immune system to maintain immune function [66], because factors in the neonatal period, such as Caesarean delivery, breastfeeding and antibiotic use, are associated with increased incidence of asthma and allergic disease. Debate continues regarding the relative importance of sources of microbial exposure, including microbe diversity and key species, during both early development and later life [60, 61, 65]. Metagenomics sequencing indicates that heritability also plays a role in the intestinal microbiome, in contrast to that of the skin [67].

Recent findings on the effects of chronic malnutrition in children provide further support to the importance of microbial diversity in the gastrointestinal microbiome, relating the macro-level effect of lacking food diversity [68] and quantity to resulting dysbiosis [69]. The resulting chronic inflammation of the gut leads to stunting, with consequent long-standing complex processes resulting in impaired child growth, long after adequate nutrition is made available again. The microbial dysbiosis further facilitates colonisation with pathogenic or potentially pathogenic bacteria, such as *Escherichia coli* / *Shigella* sp. and *Campylobacter* sp. This work led to a revision of the Koch’s postulates of the single microbial origin of a specific infectious disease, with the emergence of the “ecological Koch’s postulates”. The ecological Koch’s postulates recognise that the gut harbours a full ecosystem of microorganisms, forming an entity that can lead ultimately to disease, as a disease-promoting ecosystem (dysbiosis). Remarkably, dysbiotic microbiota can be found in similar composition, can be retrieved from an affected host and can be transmitted to germ-free hosts where they remain fairly stable [70].

Mechanisms regulating non-communicable disease

There is strong evidence that a child’s early environment, including maternally transferred prenatal signals, affects immune maturation, which modifies later disease risk [61]. Microbiota of the gut, skin and respiratory tract activate innate and regulatory networks, which contribute to healthy immune function [60, 71, 72]. Experimental work supports the idea that early postnatal colonisation of the intestine with microbiota self-induces temporal activation of bacterial sensors, which influence intestinal barrier function and humoral immunity [73]. Commensal microbes use toll-like receptor signals to maintain mucosal homeostasis [74], and regulation of intestinal permeability is affected by microbial shifts associated with low-grade inflammation [62]. Animal models indicate that cellular communication occurs through protein inducers; however, current understanding of the role of microbial colonisation dynamics is limited [75].

Bi-directional axes communicate between the gut microbiome and the brain, as well as between the skin microbiome and the lung, including direct and indirect immune, humoral and neural mechanisms [59, 71, 76]. The nervous system and pulmonary immune responses play important signalling roles related to normal function versus disease states, but current experimental studies only investigated single microbial niches, whereas it is highly likely that microbial complexity affects multiple niches [59, 77].

Expanding on the biochemical, immunological and microbial effects of biodiversity on non-communicable diseases, there is growing body of knowledge on the positive effects of nature on human mental health and wellbeing [78]. The Intergovernmental Science-Policy Platform for Biodiversity and Ecosystem Services (IPBES) has named these benefits and services as Nature’s Contributions to People (NCP) [79]. Besides the material benefits of nature, such as food and building material, there are numerous non-material benefits. For example, good access to vegetated areas is related to better cognitive function, fewer symptoms of depression, lower stress and lower risk of psychiatric dis-

orders. A most recent and compelling example is that bird species richness is positively associated with life satisfaction across Europe [80].

Challenges

Heterogeneity

A main challenge in assessing links between biodiversity and health is the vast heterogeneity encountered. There is wide variation in the definitions used for health and, particularly, for biodiversity [2, 33, 60], often related to the level of variability considered, which makes comparisons difficult or impossible. Few studies considered direct measures, with nearly all looking at indirect proxy indicators for biodiversity [3, 14, 27, 50]. A third important heterogeneity was found in study type, which encompassed modelling studies [26], including multi-host and network-based, and comparative observational studies [23]. Laboratory-based experiments [3] and applied field studies in natural systems [2] were few and had small sample sizes (table S1 in the appendix).

Complexity

Complexity was an often cited theme in the studies and review articles included. An understanding of relevant ecology is considered crucial, but generally remains incomplete owing to the myriad interactions and dynamic nature of the systems [49, 81]. Use of multi-host species epidemiological models indicates that finding generalisable diversity-disease patterns across host-pathogen systems in the field is more difficult than previously appreciated [40]. Disease transmission dynamics can be both density and frequency dependent, with consideration of biology and behaviour of hosts, vectors and pathogens [12, 15, 16, 81, 82], resulting in a high degree of variation and complexity. For example, Dobson and Auld [83] differentiate between biting insects that typically take multiple small blood meals and most ticks, which typically take only three large blood meals throughout adult life. In the context of dilution, wasted bites are far more influential in disease transmission for tick-borne than for insect-borne pathogens. Human behaviour adds additional complexity [84], which is more widely represented by social context [49] and global anthropogenic trends with environmental impacts, such climate change, nutrient pollution, protracted political/armed conflict and economic collapse [42, 85]. Untangling specific interactions in a temporal and spatial context and understanding transmission dynamics remains a major challenge.

Uncertainty and contrasting evidence

Several studies noted uncertainty [71, 84, 86], lack of convincing field evidence [19], lack of validation criteria [87] or failure to consider confounding [85]. Others described limitations precluding determination of causality, including the need for temporal studies [23], the difficulty in decoupling change in socioeconomic status from health status changes [2], and the likely non-linearity of diversity-disease risk relationships [3, 30, 52]. Investigators noted that evidence was mixed [88] or even contrasting [87]. Both complexity of transmission dynamics [25, 37, 89] and spatial scale were suggested as explanatory [27]. For example, an important distinction is the concept of hazard,

such as the presence of a pathogen in an environment, versus risk, such as the probability of being infected. Risk is relevant from a health perspective. Biodiversity drivers, notably those influenced by anthropogenic change, for example, land use, likely act differently in transmission of endemic pathogens than they do for disease emergence in humans [85]. A recent review of disease ecology studies catalogued sources of uncertainty into six broad overlapping categories: intrinsic biological factors associated with host-pathogen interaction; demographic misclassification of hosts; incomplete taxonomic knowledge on host-pathogen systems; mismatch in sampling scales; imprecision in diagnostic methods; and additional environmental modifying effects within each of the categories [90]. The authors concluded that appropriate sampling and analytical methods could account for or minimise the influence of uncertainty. An additional criticism noted was publication bias [87], identified as bias towards publishing reports of a negative relationship between biodiversity and disease [91].

Key findings

None of 155 reviewed studies documented *causal* evidence for a mechanism linking biodiversity and human health.

Infectious diseases

Dilution and amplification are the two main mechanisms thought to influence the effect of biodiversity on transmission. Numerous natural and anthropogenic drivers regulate host abundance and population density. Scale, both spatial and temporal, highly impacts diversity-disease relationships.

Non-communicable diseases

The “biodiversity hypothesis” states that lack of exposure to microbial diversity in natural environments leads to imbalance of human commensal microbiota, immune dysfunction and clinical disease. There is strong evidence that a child’s early environment, including maternally transferred prenatal signals, affects immune maturation, modifying later disease risk.

Challenges

There are widely heterogeneous definitions, approaches and methods used between biodiversity and health research areas. Complexity of ecology and variability of human demographic, socioeconomic and cultural systems contribute to uncertainty in research results.

Conclusions

None of the 155 studies reviewed documented causal evidence for a mechanism linking biodiversity and human health. A main finding is the variability and complexity of the links between biodiversity and health, depending on disease system, local ecology and probably also human social context [27, 49], although the latter was not a focus of this review. The interactive relationships between biodiversity, disease risk/transmission and anthropogenic change are important, and, although difficult to account for, must be considered [49, 85]. The relevance of local scale [92] is perhaps not a surprising finding, but may

counter current thinking that “bigger data” is necessarily better.

Future research agenda

Based on the reviewed body of evidence linking biodiversity to human infectious and non-communicable disease, a future research agenda to determine the net effects of diversity must include integrative approaches to combine different perspectives [27, 52]. A recent study on Chaga's disease developed two species-distribution models and combined them with national health data to analyse a causality assumption and investigate consistency across scales [28]. Although species composition better predicted the observed pattern of Chaga's disease occurrence than did species richness, only 5% of the variability was explained. The authors concluded that macroecology of infectious diseases must go further than analysis of biodiversity patterns and consider human infection as part of the ecological system. As we described above for directly transmitted infectious diseases, human exposure can be quite variable and is dependent on a given agro-ecosystem. Species distribution models must be appropriately utilised to accurately predict infection rates. Utilising landscape scale epidemiology would allow consideration of local scale, transmission dynamics and biogeographical regionality [49]. However, observational approaches need to be combined with experimental manipulation in communities and models that include community feedbacks across gradients incorporating natural ecosystems [36, 84]. Cost-effectiveness and cost-benefit analyses are often missing, yet crucially needed by policy makers in order to make key decisions [18]. Innovative, strategic responses will require interdisciplinary approaches. The Rockefeller Foundation-Lancet Commission on planetary health reviewed the scientific basis linking human health to the underlying integrity of the Earth's natural systems and identified substantial gaps in knowledge related to improving planetary health, including human health [93]. Their report concluded with recommendations to develop a holistic integrated research agenda, including proposals to address conceptual, research/informational and governance challenges. Our review indicates that this scientific knowledge gap still exists, in particular regarding scientific evidence for specific links between biodiversity and human infectious and non-communicable disease to characterise identifiable relationships.

Implications for policy

Although studies on the interface between biodiversity and health have increased understanding of how changes in biological diversity affect health outcomes, there is still not sufficient reliable evidence to robustly inform environmental and health policies [18, 94]. Although many policy decisions are made at national level, in order to be an effective lever for improving public health, engagement must occur across levels because of the relevance of local scale [50, 61]. Contextual adaptation is imperative. Dialogue must be across disciplines, effectively including the diversity of knowledge of all stakeholders, to adequately address the complexity of relationships between biodiversity and health. The inclusive IPBES conceptual framework, utilising the “nature's contributions to people”

approach, specifically acknowledges the range of existing views [11]. Blending a generalising perspective with a context-specific perspective allows for co-construction of knowledge among disciplines and knowledge systems [95], which can be applied to generate more legitimate practices and translate into sustainable, equitable policies. In December 2017, the Executive Secretary of the Convention on Biological Diversity produced technical guidelines [96], which support consideration of biodiversity and ecosystem management in application of One Health approaches. The guidelines include a “State of Knowledge Review” detailing specific recommendations in 12 areas where health and biodiversity connect, and providing a road map for the future. Our review indicates that the scientific evidence on causal mechanisms between biodiversity and human infectious and non-communicable diseases is to date wholly inadequate. The post-2020 biodiversity framework should surely include resources to consider such linkages, and we suggest recommendations for action.

Recommendations for action

Improve the knowledge base on contribution of biodiversity to health

Develop evidence-based answers to open questions in interdisciplinary research programs combining different perspectives through integrative approaches [27, 52].

Harmonise methodologies and assessment methods. Include epidemiological and longitudinal studies [84].

Analyse the cost-effectiveness and cost-benefit ratios of the impact of biodiversity on human health from a life-course perspective to support decision-makers in politics and business [18].

Develop innovative, strategic solutions to improve the knowledge base through interdisciplinary contextual approaches [93].

Increase awareness of health effects of natural and near-natural environments and biodiversity [78]

Maintain dialogue across disciplines and include diversity of knowledge of all stakeholders to address complexity of relationships between biodiversity and health.

Emphasise the contribution of biodiversity in addressing priority health issues and identify facts and synergies on health benefits and risks.

Adapt communication on health benefits of biodiversity to the interests of different stakeholders.

Promote synergies by increasing policy coherence [78]

Promote knowledge development in relevant disciplines and transdisciplinary approaches to integrate into sustainable policies.

Highlight links between climate change, human health and biodiversity policies and develop cross-sectoral approaches to exploit synergies.

Develop political strategies across different spatial levels since decisions are often made nationally, but local scale impacts public health [50, 61].

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Appendix

Links between biodiversity and human infectious and non-communicable diseases: a review

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Table S1

Articles included for data extraction.

Author	Year	Title	Disease type	Study type	Sample size
Aerts, R.; Honnay, O.; Van Nieuwenhuysse, A.	2018	Biodiversity and human health: mechanisms and evidence of the positive health effects of diversity in nature and green spaces	NCD	Review	
Alkanani, A. K.; Hara, N.; Gottlieb, P. A.; Ir, D.; Robertson, C. E.; Wagner, B. D.; Frank, D. N.; Zipris, D.	2015	Alterations in Intestinal Microbiota Correlate With Susceptibility to Type 1 Diabetes	NCD	Observational	
Alves, R. R.; Rosa, I. M.	2007	Biodiversity, traditional medicine and public health: where do they meet?	NA	NA	
Aziz, Q.; Dore, J.; Emmanuel, A.; Guarner, F.; Quigley, E. M.	2013	Gut microbiota and gastrointestinal health: current concepts and future directions	NCD	Review	
Bernstein, A. S.	2014	Biological diversity and public health	NA	NA	
Bouchard, C.; Beauchamp, G.; Leighton, P. A.; Lindsay, R.; Belanger, D.; Ogden, N. H.	2013	Does high biodiversity reduce the risk of Lyme disease invasion?	Inf Dis	Observational	
Brignardello, J.; Morales, P.; Diaz, E.; Romero, J.; Brunser, O.; Gotteland, M.	2010	Pilot study: alterations of intestinal microbiota in obese humans are not associated with colonic inflammation or disturbances of barrier function	NCD	Field experimental	13
Brooks, C. P.; Zhang, H.	2010	A null model of community disassembly effects on vector-borne disease risk	Inf Dis	Model	
Casarin, R. C.; Barbagallo, A.; Meulman, T.; Santos, V. R.; Sallum, E. A.; Nociti, F. H.; Duarte, P. M.; Casati, M. Z.; Goncalves, R. B.	2013	Subgingival biodiversity in subjects with uncontrolled type-2 diabetes and chronic periodontitis	NCD	Observational	

Author	Year	Title	Disease type	Study type	Sample size
Chang, K. G.; Sullivan, W. C.; Lin, Y. H.; Su, W.; Chang, C. Y.	2016	The Effect of Biodiversity on Green Space Users' Wellbeing-An Empirical Investigation Using Physiological Evidence	NA	NA	
Chen, Y.; Chen, Z.; Guo, R.; Chen, N.; Lu, H.; Huang, S.; Wang, J.; Li, L.	2011	Correlation between gastrointestinal fungi and varying degrees of chronic hepatitis B virus infection	Inf Dis	Observational	
Chivian, E.	2001	Environment and health: 7. Species loss and ecosystem disruption the implications for human health	NA	Review	
Chivian, E.; Bernstein, A. S.	2004	Embedded in nature: human health and biodiversity	NA	NA	
Civitello, D. J.; Cohen, J.; Fatima, H.; Halstead, N. T.; Liriano, J.; McMahon, T. A.; Ortega, C. N.; Sauer, E. L.; Sehgal, T.; Young, S.; Rohr, J. R.	2015	Biodiversity inhibits parasites: Broad evidence for the dilution effect	Inf Dis	Review	
Clark, N. E.; Lovell, R.; Wheeler, B. W.; Higgins, S. L.; Depledge, M. H.; Norris, K.	2014	Biodiversity, cultural pathways, and human health: a framework	NA	NA	
Daszak, P.	2000	Emerging infectious diseases of wildlife - Threats to biodiversity and human health (vol 287, pg 443, 2000)	Inf Dis	Review	
Daszak, P.; Cunningham, A. A.; Hyatt, A. D.	2001	Anthropogenic environmental change and the emergence of infectious diseases in wildlife	Inf Dis	Review	
Daszak, P.; Zambrana-Torrel, C.; Bogich, T. L.; Fernandez, M.; Epstein, J. H.; Murray, K. A.; Hamilton, H.	2013	Interdisciplinary approaches to understanding disease emergence: the past, present, and future drivers of Nipah virus emergence	Inf Dis	Model	
Davidson, G.; Chua, T. H.; Cook, A.; Speldewinde, P.; Weinstein, P.	2019	Defining the ecological and evolutionary drivers of Plasmodium knowlesi transmission within a multi-scale framework	Inf Dis	Review	
Derne, B. T.; Fearnley, E. J.; Lau, C. L.; Paynter, S.; Weinstein, P.	2011	Biodiversity and leptospirosis risk: a case of pathogen regulation?	Inf Dis	Ecological	
Dimmitt, R. A.; Staley, E. M.; Chuang, G.; Tanner, S. M.; Soltau, T. D.; Lorenz, R. G.	2010	Role of postnatal acquisition of the intestinal microbiome in the early development of immune function	NCD	Laboratory	20
Dizney, L. J.; Ruedas, L. A.	2009	Increased Host Species Diversity and Decreased Prevalence of Sin Nombre Virus	Inf Dis	Observational	

Author	Year	Title	Disease type	Study type	Sample size
Dizney, L.; Dearing, M. D.	2016	Behavioural differences: a link between biodiversity and pathogen transmission	Inf Dis	Observational	
Dobson, A.	2004	Population dynamics of pathogens with multiple host species	Inf Dis	Model	
Dobson, A. D.; Auld, S. K.	2016	Epidemiological Implications of Host Biodiversity and Vector Biology: Key Insights from Simple Models	Inf Dis	Model	
Dore, J.; Simren, M.; Buttle, L.; Guarner, F.	2013	Hot topics in gut microbiota	NCD	Review	
Dudek, K.	2014	Impact of biodiversity on tick-borne diseases	Inf Dis	Review	
Eduardo, A. A.; Santos, L.; Reboucas, M. C.; Martinez, P. A.	2018	Patterns of vector species richness and species composition as drivers of Chagas disease occurrence in Brazil	Inf Dis	Model	
Ehrmann, S.; Ruyts, S. C.; Scherer-Lorenzen, M.; Bauhus, J.; Brunet, J. et al.	2018	Habitat properties are key drivers of <i>Borrelia burgdorferi</i> (s.l.) prevalence in <i>Ixodes ricinus</i> populations of deciduous forest fragments	Inf Dis	Observational	
Ezenwa, V. O.; Godsey, M. S.; King, R. J.; Guptill, S. C.	2006	Avian diversity and West Nile virus: testing associations between biodiversity and infectious disease risk	Inf Dis	Observational	
Giraudoux, P.; Raoul, F.; Pleydell, D.; Li, T.; Han, X.; Qiu, J.; Xie, Y.; Wang, H.; Ito, A.; Craig, P. S.	2013	Drivers of <i>Echinococcus multilocularis</i> transmission in China: small mammal diversity, landscape or climate?	Inf Dis	Ecological	
Gomez, A.; Balsari, S.; Nusbaum, J.; Heerboth, A.; Lemery, J.	2013	Perspective: Environment, biodiversity, and the education of the physician of the future	NA	NA	
Granter, S. R.; Bernstein, A.; Ostfeld, R. S.	2014	Of mice and men: lyme disease and biodiversity	Inf Dis	Model	
Granter, S. R.; Ostfeld, R. S.; Milner, D. A., Jr.	2016	Where the Wild Things Aren't: Loss of Biodiversity, Emerging Infectious Diseases, and Implications for Diagnosticians	NA	NA	
Gupta, S.; Maiden, M. C.	2001	Exploring the evolution of diversity in pathogen populations	NA	Model	
Haahtela, T.	2019	A biodiversity hypothesis	NCD	Review	
Haahtela, T.; Holgate, S.; Pawankar, R.; Akdis, C. A.; Benjaponpitak, S.; Caraballo, L.; Demain, J.; Portnoy, J.; von Hertzen, L.	2013	The biodiversity hypothesis and allergic disease: world allergy organization position statement	NCD	NA	

Author	Year	Title	Disease type	Study type	Sample size
Hanski, I.; von Hertzen, L.; Fyhrquist, N.; Koskinen, K.; Torppa, K.; Laatikainen, T.; Karisola, P.; Auvinen, P.; Paulin, L.; Makela, M. J.; Vartiainen, E.; Kosunen, T. U.; Alenius, H.; Haahtela, T.	2012	Environmental biodiversity, human microbiota, and allergy are interrelated	NCD	Ecological	
Harvell, C. D.; Mitchell, C. E.; Ward, J. R.; Altizer, S.; Dobson, A. P.; Ostfeld, R. S.; Samuel, M. D.	2002	Climate warming and disease risks for terrestrial and marine biota	NA	NA	
Hosseini, P. R.; Mills, J. N.; Prieur-Richard, A. H.; Ezenwa, V. O.; Bailly, X.; Rizzoli, A.; Suzan, G.; Vittecoq, M.; Garcia-Pena, G. E.; Daszak, P.; Guegan, J. F.; Roche, B.	2017	Does the impact of biodiversity differ between emerging and endemic pathogens? The need to separate the concepts of hazard and risk	NA	NA	
Hough, R. L.	2014	Biodiversity and human health: evidence for causality?	NA	Review	
Huang, Z. Y. X.; Yu, Y.; van Langevelde, F.; De Boer, W. F.	2017	Does the dilution effect generally occur in animal diseases?	Inf Dis	Review	
Huang, Z. Y.; de Boer, W. F.; van Langevelde, F.; Olson, V.; Blackburn, T. M.; Prins, H. H.	2013	Species' life-history traits explain interspecific variation in reservoir competence: a possible mechanism underlying the dilution effect	Inf Dis	Observational	
Huang, Z. Y.; de Boer, W. F.; van Langevelde, F.; Xu, C.; Ben Jebara, K.; Berlingieri, F.; Prins, H. H.	2013	Dilution effect in bovine tuberculosis: risk factors for regional disease occurrence in Africa	Inf Dis	Model	
Huang, Z. Y.; F, V. A. N. Langevelde; Estrada-Pena, A.; Suzan, G.; WF, D. E. Boer	2016	The diversity-disease relationship: evidence for and criticisms of the dilution effect	Inf Dis	Review	
Huynen, M. M.; Martens, P.; De Groot, R. S.	2004	Linkages between biodiversity loss and human health: a global indicator analysis	NA	Observational	
Idrovo, A. J.	2011	Physical environment and life expectancy at birth in Mexico: an eco-epidemiological study	NA	Ecological	
Johnson, P. T. J.; Lund, P. J.; Hartson, R. B.; Yoshino, T. P.	2009	Community diversity reduces <i>Schistosoma mansoni</i> transmission, host pathology and human infection risk	Inf Dis	Laboratory	200
Johnson, P. T.; Preston, D. L.; Hoverman, J. T.; Henderson, J. S.; Paull, S. H.; Richgels, K. L.; Redmond, M. D.	2012	Species diversity reduces parasite infection through cross-generational effects on host abundance	Inf Dis	Field Experimental	320
Johnson, P. T.; Thielges, D. W.	2010	Diversity, decoys and the dilution effect: how ecological communities affect disease risk	Inf Dis	Review	

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Karkman, A.; Lehtimäki, J.; Ruokolainen, L.	2017	The ecology of human microbiota: dynamics and diversity in health and disease	NCD	Review	
Karvonen, A. M.; Hyvärinen, A.; Gehring, U.; Korppi, M.; Doekes, G.; Riedler, J.; Braun-Fahrlander, C.; Bitter, S.; Schmid, S.; Keski-Nisula, L.; Roponen, M.; Kaulek, V.; Dalphin, J. C.; Pfefferle, P. I.; Renz, H.; Buchele, G.; von Mutius, E.; Pekkanen, J.	2012	Exposure to microbial agents in house dust and wheezing, atopic dermatitis and atopic sensitization in early childhood: a birth cohort study in rural areas	NCD	Observational	
Keesing, F.; Belden, L. K.; Daszak, P.; Dobson, A.; Harvell, C. D.; Holt, R. D.; Hudson, P.; Jolles, A.; Jones, K. E.; Mitchell, C. E.; Myers, S. S.; Bogich, T.; Ostfeld, R. S.	2010	Impacts of biodiversity on the emergence and transmission of infectious diseases	Inf Dis	Review	
Keesing, F.; Brunner, J.; Duerr, S.; Killilea, M.; Logiudice, K.; Schmidt, K.; Vuong, H.; Ostfeld, R. S.	2009	Hosts as ecological traps for the vector of Lyme disease	Inf Dis	Laboratory	74
Keesing, F.; Ostfeld, R. S.	2015	Ecology. Is biodiversity good for your health?	Inf Dis	NA	
Keniger, L. E.; Gaston, K. J.; Irvine, K. N.; Fuller, R. A.	2013	What are the benefits of interacting with nature?	NA	Review	
Kilpatrick, A. M.; Salkeld, D. J.; Titcomb, G.; Hahn, M. B.	2017	Conservation of biodiversity as a strategy for improving human health and well-being	NA	Review	
Kirk, M.	2002	The impact of globalization and environmental change on health: challenges for nurse education	NA	Review	
Kock, R.	2014	Drivers of disease emergence and spread: is wildlife to blame?	Inf Dis	Review	
Lachish, S.; Murray, K. A.	2018	The Certainty of Uncertainty: Potential Sources of Bias and Imprecision in Disease Ecology Studies	NA	Review	
Lajaunie, C.; Morand, S.; Binot, A.	2015	The Link Between Health and Biodiversity in Southeast Asia Through the Example of Infectious Diseases	Inf Dis	NA	
Laporta, G. Z.; Lopez de Prado, P. I.; Kraenkel, R. A.; Coutinho, R. M.; Sallum, M. A.	2013	Biodiversity can help prevent malaria outbreaks in tropical forests	Inf Dis	Model	
Lepage, P.; Hasler, R.; Spehlmann, M. E.; Rehman, A.; Zvirbliene, A.; Begun, A.; Ott, S.; Kupcinskis, L.; Dore, J.; Raedler, A.; Schreiber, S.	2011	Twin study indicates loss of interaction between microbiota and mucosa of patients with ulcerative colitis	NCD	Observational	
Levi, Taal; Massey, A. L.; Holt, R. D.; Keesing, F.; Ostfeld, R. S.; Peres, C. A.	2016	Does biodiversity protect humans against infectious disease? Comment	Inf Dis	NA	

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Levy, S.	2013	The Lyme disease debate: host biodiversity and human disease risk	Inf Dis	NA	
Logan, A. C.; Jacka, F. N.; Prescott, S. L.	2016	Immune-Microbiota Interactions: Dysbiosis as a Global Health Issue	NCD	Review	
LoGiudice, K.; Ostfeld, R. S.; Schmidt, K. A.; Keesing, F.	2003	The ecology of infectious disease: effects of host diversity and community composition on Lyme disease risk	Inf Dis	Observational	
Lou, Y.; Wu, J.; Wu, X.	2014	Impact of biodiversity and seasonality on Lyme-pathogen transmission	Inf Dis	Model	
Lovell, R.; Wheeler, B. W.; Higgins, S. L.; Irvine, K. N.; Depledge, M. H.	2014	A systematic review of the health and well-being benefits of biodiverse environments	NA	Review	
Lucas Lopez, R.; Grande Burgos, M. J.; Galvez, A.; Perez Pulido, R.	2017	The human gastrointestinal tract and oral microbiota in inflammatory bowel disease: a state of the science review	NCD	Review	
Lucey, M.	2017	Urban biodiversity affects children's respiratory health	NCD	NA	
Luis, A. D.; Kuenzi, A. J.; Mills, J. N.	2018	Species diversity concurrently dilutes and amplifies transmission in a zoonotic host-pathogen system through competing mechanisms	Inf Dis	Model	
Maillard, J. C.; Gonzalez, J. P.	2006	Biodiversity and emerging diseases	Inf Dis	NA	
Manguin, S.; Boete, C.	2011	Global Impact of Mosquito Biodiversity, Human Vector-Borne Diseases and Environmental Change	Inf Dis	Review	
Marteau, P.	2009	Bacterial flora in inflammatory bowel disease	NCD	Review	
Marteau, P.; Chaput, U.	2011	Bacteria as trigger for chronic gastrointestinal disorders	NCD	Review	
McCallum, H.	2012	Disease and the dynamics of extinction	Inf Dis	Review	
McCallum, H. I.	2015	Lose biodiversity, gain disease	Inf Dis	NA	
McFarlane, R.; Sleight, A.; McMichael, T.	2012	Synanthropy of wild mammals as a determinant of emerging infectious diseases in the Asian-Australasian region	Inf Dis	Review	

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Michail, S.; Durbin, M.; Turner, D.; Griffiths, A. M.; Mack, D. R.; Hyams, J.; Leleiko, N.; Kenche, H.; Stolfi, A.; Wine, E.	2012	Alterations in the gut microbiome of children with severe ulcerative colitis	NCD	Observational	
Mihaljevic, J. R.; Joseph, M. B.; Orlofske, S. A.; Paull, S. H.	2014	The scaling of host density with richness affects the direction, shape, and detectability of diversity-disease relationships	Inf Dis	Model	
Miller, E.; Huppert, A.	2013	The effects of host diversity on vector-borne disease: the conditions under which diversity will amplify or dilute the disease risk	Inf Dis	Model	
Mindell, D. P.	2009	Sustaining Life How Human Health Depends on Biodiversity	NA	NA	
Molyneux, D. H.	2003	Common themes in changing vector-borne disease scenarios	Inf Dis	Review	
Morand, S.	2011	Infectious Diseases, Biodiversity and Global Changes: How the Biodiversity Sciences May Help	Inf Dis	Review	
Morand, S.; Guegan, J. F.	2008	How the biodiversity sciences may aid biological tools and ecological engineering to assess the impact of climatic changes	Inf Dis	Review	
Morand, S.; Jittapalapong, S.; Suputtamongkol, Y.; Abdullah, M. T.; Huan, T. B.	2014	Infectious diseases and their outbreaks in Asia-Pacific: biodiversity and its regulation loss matter	Inf Dis	Ecological	
Morris, K.	2011	How biodiversity safeguards against infectious disease	Inf Dis	NA	
Mosca, A.; Leclerc, M.; Hugot, J. P.	2016	Gut Microbiota Diversity and Human Diseases: Should We Reintroduce Key Predators in Our Ecosystem?	NCD	Review	
Noor, S. O.; Ridgway, K.; Scovell, L.; Kemsley, E. K.; Lund, E. K.; Jamieson, C.; Johnson, I. T.; Narbad, A.	2010	Ulcerative colitis and irritable bowel patients exhibit distinct abnormalities of the gut microbiota	NCD	Observational	
Ogden, N. H.; Tsao, J. I.	2009	Biodiversity and Lyme disease: dilution or amplification?	Inf Dis	Model	
Olwoch, J. M.; Reyers, B.; van Jaarsveld, A. S.	2009	Host-parasite distribution patterns under simulated climate: implications for tick-borne diseases	Inf Dis	Model	
Ostfeld, R. S.	2009	Biodiversity loss and the rise of zoonotic pathogens	Inf Dis	Review	

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Ostfeld, R. S.; Keesing, F.	2000	Biodiversity and disease risk: The case of lyme disease	Inf Dis	Model	
Ostfeld, R. S.; Keesing, F.	2013	Straw men don't get Lyme disease: response to Wood and Lafferty	Inf Dis	NA	
Ostfeld, R. S.; Keesing, F.	2012	Effects of Host Diversity on Infectious Disease	Inf Dis	Review	
Ostfeld, R. S.; Keesing, F.	2017	Is biodiversity bad for your health ?	Inf Dis	Review	
Ostfeld, R. S.; LoGiudice, K.	2003	Community disassembly, biodiversity loss, and the erosion of an ecosystem service	Inf Dis	Model	
Ostfeld, R.; Keesing, F.	2000	The function of biodiversity in the ecology of vector-borne zoonotic diseases	Inf Dis	Review	
Ott, S. J.; Kuhbacher, T.; Musfeldt, M.; Rosenstiel, P.; Hellmig, S.; Rehman, A.; Drews, O.; Weichert, W.; Timmis, K. N.; Schreiber, S.	2008	Fungi and inflammatory bowel diseases: Alterations of composition and diversity	NCD	Observational	
Packey, C. D.; Sartor, R. B.	2009	Commensal bacteria, traditional and opportunistic pathogens, dysbiosis and bacterial killing in inflammatory bowel diseases	NCD	Review	
Palo, R. T.	2014	Tick-Borne Encephalitis Transmission Risk: Its Dependence on Host Population Dynamics and Climate Effects	Inf Dis	Model	
Pastoret, P. P.; Bennett, M.; Brochier, B.; Akakpo, A. J.	2000	Animals, public health and the example of cowpox	Inf Dis	Review	
Patil, R.R.; Kumar, C.S.; Bagvandas, M.	2018	Biodiversity loss: Public health risk of disease spread and epidemics	Inf Dis	Review	
Pecl, G. T.; Araujo, M. B.; Bell, J. D.; Blanchard, J.; Bonebrake, T. C.; Chen, I. C.; Clark, T. D.; Colwell, R. K.; Danielsen, F.; Evengard, B.; Falconi, L.; Ferrier, S.; Frusher, S.; Garcia, R. A.; Griffis, R. B.; Hobday, A. J.; Janion-Scheepers, C.; Jarzyna, M. A.; Jennings, S.; Lenoir, J.; Linnetved, H. I.; Martin, V. Y.; McCormack, P. C.; McDonald, J.; Mitchell, N. J.; Mustonen, T.; Pandolfi, J. M.; Pettorelli, N.; Popova, E.; Robinson, S. A.; Scheffers, B. R.; Shaw, J. D.; Sorte, C. J.; Strugnell, J. M.; Sunday, J. M.; Tuanmu, M. N.; Verges, A.; Villanueva, C.; Wernberg, T.; Wapstra, E.; Williams, S. E.	2017	Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being	NA	Review	
Pelley, J.	2009	Biodiversity is good for your health	Inf Dis	NA	

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Pett, T. J.; Shwartz, A.; Irvine, K. N.; Dallimer, M.; Davies, Z. G.	2016	Unpacking the People-Biodiversity Paradox: A Conceptual Framework	NA	NA	
Polley, L.	2005	Navigating parasite webs and parasite flow: emerging and re-emerging parasitic zoonoses of wildlife origin	Inf Dis	Review	
Pongsiri, M. J.; Roman, J.; Ezenwa, V. O.; Goldberg, T. L.; Koren, H. S.; Newbold, S. C.; Ostfeld, R. S.; Pattanayak, S. K.; Salkeld, D. J.	2009	Biodiversity Loss Affects Global Disease Ecology	NA	Review	
Prescott, S. L.; Larcombe, D. L.; Logan, A. C.; West, C.; Burks, W.	2017	The skin microbiome: impact of modern environments on skin ecology, barrier integrity, and systemic immune programming	NCD	Review	
Randolph, S. E.; Dobson, A. D.	2012	Pangloss revisited: a critique of the dilution effect and the biodiversity-buffers-disease paradigm	Inf Dis	Review	
Riiser, A.	2015	The human microbiome, asthma, and allergy	NCD	Review	
Roche, B.; Dobson, A. P.; Guegan, J. F.; Rohani, P.	2012	Linking community and disease ecology: the impact of biodiversity on pathogen transmission	Inf Dis	Model	
Roche, B.; Guegan, J. F.	2011	Ecosystem dynamics, biological diversity and emerging infectious diseases	Inf Dis	Review	
Roche, B.; Rohani, P.; Dobson, A. P.; Guegan, J. F.	2013	The impact of community organization on vector-borne pathogens	Inf Dis	Model	
Rohr, J. R.; Raffel, T. R.; Blaustein, A. R.; Johnson, P. T.; Paull, S. H.; Young, S.	2013	Using physiology to understand climate-driven changes in disease and their implications for conservation	Inf Dis	Model	
Rook, G. A.	2013	Regulation of the immune system by biodiversity from the natural environment: an ecosystem service essential to health	NCD	NA	
Ruokolainen, L.; Fyhrquist, N.; Haahtela, T.	2016	The rich and the poor: environmental biodiversity protecting from allergy	NCD	Review	
Ruyts, S. C.; Landuyt, D.; Ampoorter, E.; Heylen, D.; Ehrmann, S.	2018	Low probability of a dilution effect for Lyme borreliosis in Belgian forests	Inf Dis	Observational	

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Salkeld, D. J.; Lane, R. S.	2010	Community ecology and disease risk: lizards, squirrels, and the Lyme disease spirochete in California, USA	Inf Dis	Model	
Salkeld, D. J.; Padgett, K. A.; Jones, J. H.	2013	A meta-analysis suggesting that the relationship between biodiversity and risk of zoonotic pathogen transmission is idiosyncratic	Inf Dis	Review	
Salkeld, D. J.; Padgett, K. A.; Jones, J. H.; Antolin, M. F.	2015	Public health perspective on patterns of biodiversity and zoonotic disease	Inf Dis	NA	
Sattenspiel, L.	2000	Tropical environments, human activities, and the transmission of infectious diseases	Inf Dis	Review	
Schaub, B.; Vercelli, D.	2015	Environmental protection from allergic diseases: From humans to mice and back	NCD	Review	
Schippa, S.; Iebba, V.; Barbato, M.; Di Nardo, G.; Totino, V.; Checchi, M. P.; Longhi, C.; Maiella, G.; Cucchiara, S.; Conte, M. P.	2010	A distinctive 'microbial signature' in celiac pediatric patients	NCD	Observational	
Schmidt, K. A.; Ostfeld, R. S.	2001	Biodiversity and the dilution effect in disease ecology	Inf Dis	Model	
Seksik, P.; Rigottier-Gois, L.; Gramet, G.; Sutren, M.; Pochart, P.; Marteau, P.; Jian, R.; Dore, J.	2003	Alterations of the dominant faecal bacterial groups in patients with Crohn's disease of the colon	NCD	Observational	
Shanahan, F.	2009	Linking lifestyle with microbiota and risk of chronic inflammatory disorders	NCD	Review	
Simpson, J. E.; Hurtado, P. J.; Medlock, J.; Molaei, G.; Andreadis, T. G.; Galvani, A. P.; Diuk-Wasser, M. A.	2012	Vector host-feeding preferences drive transmission of multi-host pathogens: West Nile virus as a model system	Inf Dis	Model	
Sintayehu, D. W.; Heitkonig, I. M. A.; Prins, H. H. T.; Tessema, Z. K.; De Boer, W. F.	2017	Effect of host diversity and species assemblage composition on bovine tuberculosis (bTB) risk in Ethiopian cattle	Inf Dis	Observational	
Sparagano, O. A.; De Luna, C. J.	2008	From population structure to genetically-engineered vectors: new ways to control vector-borne diseases?	Inf Dis	Review	

Author	Year	Title	Disease type	Study type	Sample size
States, S. L.; Brinkerhoff, R. J.; Carpi, G.; Steeves, T. K.; Folsom-O'Keefe, C.; DeVeaux, M.; Diuk-Wasser, M. A.	2014	Lyme disease risk not amplified in a species-poor vertebrate community: similar <i>Borrelia burgdorferi</i> tick infection prevalence and OspC genotype frequencies	Inf Dis	Observational	
Stephens, C.	2012	Biodiversity and global health-hubris, humility and the unknown	NA	NA	
Stephens, C.; Athias, R.	2015	Focus on biodiversity, health and wellbeing	NA	NA	
Sutherst, R. W.	2001	The vulnerability of animal and human health to parasites under global change	Inf Dis	Model	
Suzaki, H.; Watanabe, S.; Pawankar, R.	2013	Rhinosinusitis and asthma-microbiome and new perspectives	NCD	Review	
Suzan, G.; Marce, E.; Giermakowski, J. T.; Armien, B.; Pascale, J.; Mills, J.; Ceballos, G.; Gomez, A.; Aguirre, A. A.; Salazar-Bravo, J.; Armien, A.; Parmenter, R.; Yates, T.	2008	The effect of habitat fragmentation and species diversity loss on hantavirus prevalence in Panama	Inf Dis	Model	
Swaddle, J. P.; Calos, S. E.	2008	Increased avian diversity is associated with lower incidence of human West Nile infection: observation of the dilution effect	Inf Dis	Ecological	
Thieltges, D. W.; Jensen, K. T.; Poulin, R.	2008	The role of biotic factors in the transmission of free-living endohelminth stages	Inf Dis	Review	
Thongsripong, P.; Green, A.; Kittayapong, P.; Kapan, D.; Wilcox, B.; Bennett, S.	2013	Mosquito vector diversity across habitats in central Thailand endemic for dengue and other arthropod-borne diseases	Inf Dis	Observational	
Tischer, C. G.; Heinrich, J.	2013	Exposure assessment of residential mould, fungi and microbial components in relation to children's health: achievements and challenges	NCD	Review	
Tonmoy, F. N.; El-Zein, A.; Hinkel, J.	2014	Assessment of vulnerability to climate change using indicators: a meta-analysis of the literature	NA	Review	
Veterinary Record	2004	Extinction by infection? Effects of disease on biodiversity	NA	NA	
von Hertzen, L.; Beutler, B.; Bienenstock, J.; Blaser, M.; Cani, P. D.; Eriksson, J.; Farkkila, M.; Haahtela, T.; Hanski, I.; Jenmalm, M. C.; Kere, J.; Knip, M.; Kontula, K.; Koskenvuo, M.; Ling, C.; Mandrup-Poulsen, T.; von Mutius, E.; Makela, M. J.;	2015	Helsinki alert of biodiversity and health	NCD	NA	

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Paunio, T.; Pershagen, G.; Renz, H.; Rook, G.; Saarela, M.; Vaarala, O.; Veldhoen, M.; de Vos, W. M.					
Vora, N.	2008	Impact of anthropogenic environmental alterations on vector-borne diseases	Inf Dis	Review	
Vourc'h, G.; Plantard, O.; Morand, S.	2012	How Does Biodiversity Influence the Ecology of Infectious Disease?	Inf Dis	NA	
Werden, L.; Barker, I. K.; Bowman, J.; Gonzales, E. K.; Leighton, P. A.; Lindsay, L. R.; Jardine, C. M.	2014	Geography, deer, and host biodiversity shape the pattern of Lyme disease emergence in the Thousand Islands Archipelago of Ontario, Canada	Inf Dis	Observational	
West, C. E.; Renz, H.; Jenmalm, M. C.; Kozyrskyj, A. L.; Allen, K. J.; Vuillermin, P.; Prescott, S. L.	2015	The gut microbiota and inflammatory noncommunicable diseases: associations and potentials for gut microbiota therapies	NCD	Review	
Wollina, U.	2017	Microbiome in atopic dermatitis	NCD	Review	
Wood, C. L.; Lafferty, K. D.	2013	Biodiversity and disease: a synthesis of ecological perspectives on Lyme disease transmission	Inf Dis	Review	
Wood, C. L.; Lafferty, K. D.; DeLeo, G.; Young, H. S.; Hudson, P. J.; Kuris, A. M.	2016	Does biodiversity protect humans against infectious disease? Reply	Inf Dis	NA	
Wood, C. L.; Lafferty, K. D.; DeLeo, G.; Young, H. S.; Hudson, P. J.; Kuris, A. M.	2014	Does biodiversity protect humans against infectious disease?	Inf Dis	Review	
Wood, C. L.; McInturff, A.; Young, H. S.; Kim, D.; Lafferty, K. D.	2017	Human infectious disease burdens decrease with urbanization but not with biodiversity	Inf Dis	Ecological	
Young, H. S.; Wood, C. L.; Kilpatrick, A. M.; Lafferty, K. D.; Nunn, C. L.; Vincent, J. R.	2017	Conservation, biodiversity and infectious disease: scientific evidence and policy implications	Inf Dis	NA	
Zargar, U. R.; Chishti, M. Z.; Ahmad, F.; Rather, M. I.	2015	Does alteration in biodiversity really affect disease outcome? - A debate is brewing	Inf Dis	NA	

Key:

Inf Dis: infectious disease

NA: not classifiable

NCD: non communicable disease