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Exploring connections among nature, biodiversity, ecosystem services, and human health and well-being: Opportunities to enhance health and biodiversity conservation ☆

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We are at a key juncture in history where biodiversity loss is occurring daily and accelerating in the face of population growth, climate change, and rampant development. Simultaneously, we are just beginning to appreciate the wealth of human health benefits that stem from experiencing nature and biodiversity. Here we assessed the state of knowledge on relationships between human health and nature and biodiversity, and prepared a comprehensive listing of reported health effects. We found strong evidence linking biodiversity with production of ecosystem services and between nature exposure and human health, but many of these studies were limited in rigor and often only correlative. Much less information is available to link biodiversity and health. However, some robust studies indicate that exposure to microbial biodiversity can improve health, specifically in reducing certain allergic and respiratory diseases. Overall, much more research is needed on mechanisms of causation. Also needed are a re-envisioning of land-use planning that places human well-being at the center and a new coalition of ecologists, health and social scientists and planners to conduct research and develop policies that promote human interaction with nature and biodiversity. Improvements in these areas should enhance human health and ecosystem, community, as well as human resilience.

Contents

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1. Introduction

Human health and well-being can be considered the ultimate or cumulative ecosystem service (Sandifer and Sutton-Grier, 2014). For medical practitioners and the public, health often is thought of narrowly as the absence of disease. However, the World Health Organization (WHO, 1946) defines health much more broadly as "… a state of physical, mental and social well-being and not merely the absence of disease or infirmity." Health, or health and well-being, are also described as including a supportive environment, personal security, freedom of choice, social relationships, adequate employment and income, access to educational resources, and cultural identity (Diaz et al., 2006; MA (Millennium Assessment) 2005). Here we use these latter definitions to encompass the breadth of factors that together comprise human health and well-being.

Just as we are beginning to appreciate the variety and complexity of human health benefits that stem from experiencing nature and, more specifically, biodiversity, we are reaching a critical point in human history where biodiversity and habitat losses are accelerating due to increased human use, climate change, and rampant development. Strengthening the focus of nascent science efforts in this area on a much deeper understanding of nature–biodiversity–ecosystem service–health linkages could play a critical role in supporting growing policy efforts to incorporate more natural areas and biodiversity in the design and protection of our cities and coastal communities, with concomitant public health benefits.

In this paper, we explore observed and potential connections among nature, biodiversity, ecosystem services and human health and well-being, through biodiversity–ecosystem services linkages, associations of nature with human health, and recent limited evidence relating biodiversity to some human health outcomes based on a review of selected literature. We used the generally accepted definition of nature as the physical and biological world not manufactured or developed by people. We were interested in the health effects of human exposure to natural elements such as plants and other living things, natural areas including coastlines and mountains, natural and semi-natural environments such as parks and managed forests and wildlife sanctuaries, and undeveloped landscapes, seascapes and, in some cases, even agricultural lands. Biodiversity was also defined broadly. Based on language from the Convention on Biological Diversity (United Nations, 1992), Duffy et al. (2013) described biodiversity as "the variety of life, encompassing variation at all levels, from the genes within a species to biologically created habitat within ecosystems." Nature is not biodiversity, nor a proxy for biodiversity, but certainly encompasses biodiversity. Ecosystem services are the specific benefits people derive from nature (MA (Millennium Assessment), 2005).

We concentrated on reported and potential values of exposure to natural elements, ecosystem services, and biodiversity, to human health and well-being. In general, we noted a lack of studies that identified *causality* and *specific* mechanisms by which either nature (often meaning green space, particularly urban green space) or biodiversity supports ecological functioning and hence, the provisioning of all ecosystem services and human health and well-being (Cardinale et al., 2012). Thus, with one major exception discussed here, the actual roles of biodiversity in promoting human health and well-being remain largely uncertain. We addressed the following questions: (1) How important is biodiversity to the provision of ecosystem services? (2) Is there convincing evidence that experiencing more natural settings, even briefly or vicariously, can improve psychological and physical health? (3) Does exposure to biodiverse surroundings result in measurable health responses? (4) Can biodiversity provide humans and animals protection from infectious and/or allergic and inflammatory diseases? (5) Is there evidence that experiencing coastal nature or marine biodiversity has health effects? Based on our findings, we suggest that new research and policy strategies, involving collaboration among ecological, environmental health, biomedical, and conservation scientists as well as urban, land and coastal planners, and social scientists, are needed to make critical progress toward answering these and related questions. We conclude with ideas for key components of those strategies and recommendations for a way forward.

2. Material and methods

We conducted a broad-based but selective literature assessment as the amount of potentially relevant papers was vast and there have been several recent reviews dealing with different parts of the topic [e.g., see (Bernstein, 2014; Hough, 2014; Keniger et al., 2013)] upon which we could build effectively. We explored broadly the links among ecosystem services, nature, biodiversity and psychological and physical health and other well-being parameters, as well as human allergic and respiratory diseases. Our focus was peer-reviewed literature, particularly recent papers that provided results directly germane to our topics of health and well-being connections to nature, ecosystem services and biodiversity. To identify relevant papers, we utilized internet searches with combinations of biodiversity, ecosystem services, nature, green space, health, and related terms and extensive examination of reference lists. We consulted literature from a wide range of disciplines including ecology and ecosystem studies, public health and biomedical sciences, urban planning, psychology, and others.

We concentrated on papers that either demonstrated or failed to find associations between biodiversity and ecosystem services, and between various types of exposures to more natural and/or biodiverse environments and measures of some type of effect on human health and well-being. Further, we considered the breadth of benefits and weight of evidence for positive effects of nature and biodiversity on human health and well-being. Building on the typological work of Keniger et al. (2013) we developed a comprehensive listing of types and examples of reported health effects from exposure to nature and biodiversity and discussed research needs and ways to use existing information to enhance human health and well-being and strengthen arguments for conserving and restoring biodiversity.

3. Results

3.1. Biodiversity, ecosystem processes, and ecosystem services

It has long been recognized that human health is markedly affected by environmental conditions. Although not everyone agrees [e.g., see (Ridder, 2008)], much recent ecological literature strongly supports the hypothesis that maintaining natural biodiversity, particularly functional biodiversity (the range of functional traits demonstrated by individual species or groups of species), is fundamental to sustaining ecosystem processes, functions and the continued delivery of ecosystem services upon which human survival and welfare depend (Diaz et al., 2006; Cardinale et al., 2012; Worm et al., 2006; Beaumont et al., 2007; Delegates of The World Conference on Marine Biodiversity, 2008; Gamfeldt et al., 2013; Haines-Young and Potschin, 2010; Loreau, 2010; Loreau and de Mazancourt, 2013; Mace et al., 2012; Naeem et al., 2012; Norris, 2012; Palumbi et al., 2009; Reich et al., 2012). Diaz et al. (2006) suggested a possible general mechanism by which biodiversity supports the provision of ecosystem services: "By affecting the magnitude, pace, and temporal continuity by which energy and materials are circulated through ecosystems, biodiversity in the broad sense influences the provision of ecosystem services." Ecosystems that are stressed by a variety of factors are likely to have impaired or reduced ecosystem services, with consequent potential for negative impacts to human health and well-being (Sandifer and Sutton-Grier, 2014). While an ecosystem services approach may lead to a human-centric view of the biosphere, a focus on managing to preserve key components of ecosystems, principally natural biodiversity, responsible for delivery of services to humans should result in better long-term health of ecosystems with consequent continued delivery of services critical for survival of other species as well.

Based on our review, the significance of biodiversity to human welfare is immense. Diaz et al. (2006) stated it simply as "human societies have been built on biodiversity." A major concern of many ecologists is that the loss of biodiversity will negatively impact human access to reliable food, clean water, and raw materials (provisioning and regulating ecosystem services) (Diaz et al., 2006; Cardinale et al., 2012), and will likely have greater impact on poor and vulnerable people (Diaz et al., 2006). However, Raudsepp-Hearne et al. (2010) noted that despite degradation of some major ecosystem services, it is difficult to discern impacts to human health and well-being at the global scale. They reported that "existing global data sets strongly support the Millennium Assessment (MA (Millennium Assessment) 2005) finding that human well-being is increasing" and that overall there was only weak evidence of impacts to human well-being at the global scale. This finding should be qualified, however, to include the fact that patterns of disease are changing with the result that in the developed world issues such as obesity (Caballero, 2007) and a variety of other inflammatory-based physical and psychiatric disorders are now some of the most important public health concerns. For example, approximately 40% of children in the United Kingdom are now affected by allergic maladies (Gupta et al., 2004) as are similar numbers in the United States (Lynch et al., 2014). To a considerable extent, the inability of Raudsepp-Hearne et al. (2010) to discern human effects of degraded ecosystem services may have resulted from a lack of sufficient data at appropriate scales and/or the possibility that ecological tipping points have not been reached. It is also likely that not all the important ecosystem services, such as the significant role that environmental microbial biodiversity plays in human immune function [see (Rook, 2013) and below], were considered.

In their comprehensive review, Cardinale et al. (2012) determined that, where data are available, in most cases biodiversity is supportive of human well-being, but in other cases a relationship could not be determined due to lack of sufficient data to support strong conclusions. This data deficiency is particularly true for roles biodiversity may play to support cultural services (e.g., religious, scientific, educational, recreational and esthetic opportunities), and it is noteworthy that cultural services were excluded from their review due to a lack of data. Similarly, Raudsepp-Hearne et al. (2010) did not consider psychological health or cultural factors in their assessment of human well-being and the degradation of ecosystem services. Because socio-economic factors play such dominant roles in determining human health and well-being, Hough (2014) concluded that "Unless it is possible to decouple the positive benefits of improved socio-economic status from biodiversity, it is unlikely that a causative relationship between biodiversity loss and health will be found." In contrast, based on our assessment, we believe that the weight of evidence supports the concept that natural biodiversity sustains the delivery of many ecosystem services upon which human health and well-being depend, and hence a loss of biodiversity leads to decreases in some aspects of human health and well-being.

3.2. Human health and nature

There is a large and growing body of literature that demonstrates that contact with nature (broadly defined in the introduction and including urban green space, parks, forests, etc.) can lead to measurable psychological and physiological health benefits, as well as numerous other positive effects (Table 1). Much of the work we reviewed compared health responses in urban spaces with those observed in non-built or more natural environments, such as parks, forests, countryside, and coasts. Most of these studies did not have a direct biodiversity component, although a few did (see next section). In addition, many of these studies exhibited one or more significant weaknesses (Rook, 2013). For example, many studies lacked adequate controls, sample sizes, and duration; objective data collection instead of, or in addition to, self-reported information; comparisons beyond just "green" to urban; broad collections of physiological as well as psychological health data; statistical rigor; data on quality of and biodiversity characteristics of the "green" environment; and assessment of long-term as well as transient health effects. In addition, while a number of studies provided moderate to strong correlative information, relatively few reported on extensive epidemiological datasets or examination of potential causative relationships and mechanisms. Nevertheless, what we gleaned as exceptionally important from our assessment is the apparent generality of a wide range of positive health responses to some kind of cues from environments that are more natural, and sometimes more obviously biodiverse, than city streetscapes or workplaces (Table 1). Although there are a few studies that report no positive effects of nature exposure [e.g., (Huynh et al., 2013; Richardson et al., 2010)], these are far outweighed by evidence for positive mental and physiological health measures and general feelings of well-being. We summarized key findings from a very broad range of studies in Table 1, and discuss in more detail some of the most robust of these in the following sections.

Based on our review, experiencing nature can have positive effects on mental/psychological health, healing, heart rate, concentration, levels of stress, blood pressure, behavior, and other health factors (Brown and Grant, 2005). For example, viewing nature, even through a window, improves recovery from surgery (Ulrich, 1984), while exercise outdoors in a natural environment improves mood and self-esteem (Barton and Pretty, 2010) and is more restorative

Table 1
Typology and examples of reported health benefits of interacting with nature[a] – modified from Keniger et al. (2013) with added categories, examples, and references.

Benefits	Description	Examples	Selected references
Psychological	Positive effect on mental processes and behavior	Psychological well-being	(Catanzaro and Ekanem, 2004; Curtin, 2009; Kamitsis and Francis, 2013; Kaplan, 2001; Maller et al., 2006; Moore et al., 2006; Nisbet et al., 2011; Sugiyama et al., 2008; Pretty, 2004)
		Attention restoration/perceived restorativeness	(Hartig and Staats, 2006; Kaplan and Kaplan, 1989; Tyrvainen et al., 2014; White et al., 2010; White et al., 2013)
		Decreased depression, dejection, anger, aggression, frustration, hostility, stress	(Kuo and Sullivan, 2001a; Morita et al., 2007; Park et al., 2011)
		Increased self-esteem	(Kaplan, 1974; Maller, 2009; Pretty et al., 2007, 2005)
		Positive/improved mood	(Tyrvainen et al., 2014; Park et al., 2011; Pretty et al., 2005; Coon et al., 2011; Cracknell, 2013; Driver et al., 1991; Hartig et al., 1996; Shin et al., 2011; Ten Wolde, 1999; Tsunetsugu et al., 2013; Wyles et al., 2014; Lee et al., 2014)
		Reduced anxiety and tension	(Park et al., 2011; Pretty et al., 2005; Lee et al., 2014; Chang and Chen, 2005; Maas et al., 2009a; Song et al., 2014)
		Increased prosocial behavior/improved behavior	(Han, 2009; Zhang et al., 2014)
		Increased opportunities for reflection	(Fuller et al., 2007; Herzog et al., 1997)
		Increased vitality and vigor/decreased fatigue	(Nisbet et al., 2011; Tyrvainen et al., 2014; Park et al., 2011; Pretty et al., 2005; Song et al., 2014; Ryan et al., 2010)
		Increased creativity	(Tyrvainen et al., 2014)
		Increased happiness	(MacKerron and Mourato, 2013)
		Increased calmness, comfort and refreshment	(Park et al., 2009)
		Improved body image for women	(Hennigan, 2010)
		Reduced ADHD in children	(Kuo and Taylor, 2004; Taylor et al., 2001)
		Improved emotional, social health of children; self-worth	(Maller, 2009; Wells and Evans, 2003)
		Improved quality of life	(Song et al., 2012)
Cognitive	Positive effect on cognitive ability or function	Attentional restoration	(Fuller et al., 2007; Herzog et al., 1997; Bodin and Hartig, 2003; Han, 2010; Hartig et al., 1991)
		Reduced mental fatigue/fatigue	(Kuo and Sullivan, 2001; Park et al., 2011; Fjeld et al., 1998; Kuo, 2001)
		Reduced confusion	(Park et al., 2011; Pretty et al., 2005)
		Improved academic performance/education/learning opportunities	(Blair, 2009; Matsuoka, 2008; Taylor and Kuo, 2006; Wu et al., 2014)
		Improved cognitive function	(Shin et al., 2011; Berman et al., 2008)
		Improved cognitive function in children	(Wells, 2000)
		Improved productivity/ability to perform tasks/positive workplace attitude	(Bringslimark et al., 2007; Lottrup et al., 2013)
Physiological	Positive effect on physical function and/or physical health	Better general health	(Moore et al., 2006; de Vries et al., 2003; Maas et al., 2006; Maller et al., 2009; Mitchell and Popham, 2007)
		Perceived health/well-being	(Sugiyama et al., 2008; de Vries et al., 2003; Maas et al., 2006)
		Reduced illness/cough/mortality/sick leave	(Han, 2009; Fjeld et al., 1998; Bringslimark et al., 2007; Mitchell and Popham, 2008)
		Stress reduction/less stress-related illness/improved physiological functioning:	(Lottrup et al., 2013; Hansmann et al., 2007; Hartig et al., 2003; Moore, 1982; Parsons et al., 1998; Thompson et al., 2012; Ulrich et al., 1991; Van Den Berg and Custers, 2011; West, 1995; Yamaguchi et al., 2006)
		Reduced cortisol levels (indicative of lower stress)	(Song et al., 2014; Thompson et al., 2012; Van Den Berg and Custers, 2011; Park et al., 2007, 2010; Tsunetsugu et al., 2007)
		Reduced blood pressure	[Pretty et al., 2005; Tsunetsugu et al., 2013; Lee et al., 2014; Maas et al., 2009a–no effect, Song et al., 2014–no effect, Park et al., 2009, 2010; Tsunetsugu et al., 2007]
		Reduced mortality from circulatory and respiratory disease	(Mitchell and Popham, 2008; Villeneuve et al., 2012; Lachowycz and Jones, 2014)
		Reduced headaches/pain	(Moore et al., 2006; Hansmann et al., 2007)
		Reduced mortality due to income deprivation	(Maas et al., 2009a, 2006; de Vries et al., 2003; Mitchell and Popham, 2008; Wheeler et al., 2012)
		Reduced mortality from stroke	(Wilker et al., 2014)
		Reduced COPD, upper respiratory tract infections, asthma, other inflammatory disorders and intestinal disease	(Lynch et al., 2014; Rook, 2013, 2010; Maas et al., 2009a; Haahtela et al., 2013; Hanski et al., 2012; Debarry et al., 2007; Ege et al., 2011)
		Reduced obesity	(Astell-Burt et al., 2014a)–women only, (Pereira et al., 2013a)
		Faster healing/recovery from surgery/illness/trauma	(Ulrich, 1984)
		Improved addiction recovery	(Bennett et al., 1998)
		Reduced cardiovascular and respiratory disease	[(Pereira et al., 2013a; Richardson and Mitchell, 2010)–men only]
		Reduced pulse/heart rate	(Cracknell, 2013; Tsunetsugu et al., 2013; Lee et al., 2014; Song et al., 2014; Park et al., 2009, 2010; Tsunetsugu et al., 2007)
		Decreased sympathetic nerve activity	(Tsunetsugu et al., 2013; Lee et al., 2014; Song et al., 2014)
		Increased parasympathetic nerve activity	(Tsunetsugu et al., 2013; Lee et al., 2014; Song et al., 2014)
		Increased levels of natural killer cells and anti-cancer proteins	(Li et al., 2008a, 2008b, 2007)
		Decreased blood glucose levels in diabetes patients	(Ohtsuka et al., 1998)
		Decreased Type 2 diabetes	(Astell-Burt et al., 2014b)

Table 1 (*continued*)

Benefits	Description	Examples	Selected references
		Increased physical activity	(Bird, 2004; Depledge and Bird, 2009; Wells et al., 2007)
		Reduced exposure to pollution	(Pretty et al., 2011)
		Increased longevity	(Takano et al., 2002)
		Better health of children	(Maas et al., 2009a)
		Reduced preterm births and low birth weight	(Hystad et al., 2014)
		General health/convalescence/better health near coasts	(Wheeler et al., 2012; Fortescue Fox and Lloyd, 1938)
Disease exposure and regulation	Potential to reduce incidence of infectious diseases	Reduction in spread/amplification/of some infectious diseases including some zoonotic diseases	[(Bonds et al., 2012; Derne et al., 2011; Ezenwa et al., 2006; Keesing et al., 2006; Laporta et al., 2013; Pongsiri et al., 2009; Salkeld et al., 2013)–no effect of biodiversity, (Wood and Lafferty, 2013; Ostfeld and Keesing, 2012; Wood et al., 2014)–no general effect of biodiversity]
Social	Positive effect at individual community, or national scale	Increased/facilitated social interaction	(Coley et al., 1997; Kingsley and Townsend, 2006; Sullivan et al., 2004)
		Enables social empowerment	(Westphal, 2003)
		Reduced aggression, crime rates, violence, fear	(Kuo and Sullivan, 2001b)
		Enables interracial interaction	(Shinew et al., 2004)
		Enhances social cohesion and social support	(Moore et al., 2006; Kingsley and Townsend, 2006; Maas et al., 2009b)
Esthetic, cultural, recreational, spiritual	Positive effect on cultural and spiritual well-being	Esthetic appreciation	(Lindemann-Matthies et al., 2010)
		Increased inspiration	(Fredrickson and Anderson, 1999)
		Enhanced spiritual well-being	(Curtin, 2009; Kamitsis and Francis, 2013; Williams and Harvey, 2001)
		Increased recreational satisfaction	(Wyles et al., 2014; MacKerron and Mourato, 2013; Bird, 2004; Schuhmann et al., 2013)
Tangible materials	Material goods and benefits	Supply of food, raw materials, medicines, and other values	(Bernstein, 2014; Chivian and Bernstein, 2008; Kaplan, 1973; TEEB, 2010)
		Contribution to biomedical advances	(Bernstein, 2014; Chivian and Bernstein, 2008)
		Increased value of property/housing; money	(White et al., 2010; TEEB, 2010; Bolitzer and Netusil, 2000; Kroeger and, 2006 2008; Melichar and Kaprova, 2013; Pearson et al., 2002)
		Economic value of recreation	(Rees et al., 2010; Shrestha et al., 2007; Southwick Associates, 2011)
Increased Resiliency	Personal and community ability to withstand impacts and remain healthy	Sustainability/pro-environment awareness and behavior	(Nisbet et al., 2011, 2009; Wyles et al., 2014; Mayer and Frantz, 2004; Wyles et al., 2013)
		Supply of ecosystem services critical for human health and well-being	(Sandifer and Sutton-Grier, 2014; Diaz et al., 2006; Haines-Young and Potschin, 2010)
		Supply of ecosystem services that support communities and enable community resilience	(Sandifer and Sutton-Grier, 2014; Rogers, 2013; Tzoulas et al., 2007)

[a] Nature is defined broadly here to include plants and other living things, natural and semi-natural areas including coastlines and mountains, parks, forests, wildlife sanctuaries, views of seascapes and relatively undeveloped landscapes.

than exercise outdoors in an urban environment (Hartig et al., 2003). In another example, Coon et al. (2011) assessed the effects on mental health of short-term outdoor (natural environment) physical activity compared with physical activity indoors. In more than half of the studies reviewed, participants' mood and attitude were significantly more positive following outdoor compared to indoor activity. Participants reported greater revitalization, self-esteem, positive engagement, vitality, energy, pleasure, and delight, as well as lower frustration, worry, confusion, depression, tension, and tiredness. Similarly, a recent meta-analysis assessed changes in mental health before and after short-term exposure to facilitated outdoor exercise (Barton and Pretty, 2010) and determined that exercise in green places improved both self-esteem and mood. The type of green environment experienced affected the mental health benefits and exercise associated with waterside habitats revealed the greatest positive change for both self-esteem and mood. In addition, green spaces in urban areas have the ability to temper other factors that negatively affect human health, such as poor air quality and heat stress effects (Brown and Grant, 2005).

Some positive health effects of nature exposure were seen for all ages and both sexes, although some papers reported different responses between males and females [e.g., (Astell-Burt et al., 2014a; Richardson and Mitchell, 2010)] and sometimes more important beneficial effects in socio-economically deprived populations (Maas et al., 2009a; Lachowycz and Jones, 2014). However, these have not yet been identified widely as associated factors. Notwithstanding the fact that a number of studies demonstrate positive impacts of natural environments (or green space) on mental health and well-being, most of these studies did not empirically test for, or identify, ecological or other mechanisms that link nature or biodiversity to human health (Dean et al., 2011).

Several robust studies demonstrate associations between nature exposure and a reduction in physical disease, not just a few physiological measurements. Mitchell and Popham (2008) sampled green exposure and mortality data based on samples from the entire 2001 census population of England and utilized over 366,000 individual mortality records to evaluate potential associations between exposure to green and mortality. They found significant reductions in total mortality and that from circulatory disease for those individuals who lived in the greenest areas, including those classified as income-deprived, but they were not able to identify causal mechanism(s) for the health effects observed. In the

Netherlands, Maas et al. (2009a) used a representative sample from electronic medical records from 96 medical practices serving a population of approximately 345,000 people to examine the prevalence of 24 disease clusters and resulting mortality in relation to the amount of green space near (within 1 km) or farther away (within 3 km) from patients' homes. For 15 of the 24 disease clusters considered, the annual prevalence rate was lower where there was a higher amount of green space in a 1 km radius around the home. The study specifically documented lower prevalence for anxiety and depression (especially), upper respiratory tract infections, asthma, chronic obstructive pulmonary disorder (COPD), severe intestinal complaints, and infectious disease of the intestine. Again, while the authors discussed potential causative factors, including positive effects on mental health and stress, level of physical activity, and others, the study did not determine causality.

Wilker et al. (2014) evaluated association between green space and ischemic stroke in an epidemiological study that followed 1675 patients in the Boston, MA, USA area for up to 13 years post-stroke. They reported that those who lived in the lowest quartile of green space examined had a higher mortality rate than those in the highest green space quartile, and this effect was not linked to socioeconomic or clinical factors, but no mechanism of causality was identified. In another study, increased longevity was reported among a large cohort of elderly people (≥ 73 years) who lived in areas of Japan with significant “walkable green spaces” (Takano et al., 2002). More recently Lachowycz and Jones (2014) utilized data collected by survey from 165,424 adults in England between 2007 and 2008 to investigate whether walking could explain observed associations between decreased mortality rates and green space exposure. Their results showed that mortality-reduction effects of green space were only manifested in the most socio-economically deprived areas and were not mediated by walking in the green space. They hypothesized that other, perhaps psychosocial, factors might have more of a causal relationship, but this remains for future study.

Decreases in pre-term births and low birth weight, mortality rates, as well as increases in academic performance, have all been associated with greenness. For example, Hystad et al. (2014) followed the outcomes of nearly 65,000 singleton births in Vancouver, BC, between 1999 and 2002 in relation to satellite-derived greenness data. They reported significant positive relationship of greenness with lower incidence of very and moderately pre-term births and low birth weights, and this relationship was independent of estimated exposure to air or noise pollution, proximity to parks, or walkability of the neighborhood. In another study, Villeneuve et al. (2012) followed a cohort of $\sim$575,000 individuals from 10 Canadian cities for 22 years, during which the cohort experienced $\sim$187,000 deaths. They reported reduced mortality rates for adults who lived in areas with the most green space, and the strongest association was with non-malignant respiratory disease. Reduced mortality was observed among all age groups examined, from 35 years to >65, not just for the elderly (the focus of the Takano et al. (2002) study). However, Villeneuve et al. (2012) noted that higher income level had more of a positive association with reduced mortality than did green space, but a small green space effect was apparent across all income levels, and it was not confounded by air pollution or socio-economic factors. Finally, Wu et al. (2014) used satellite-derived greenness data to evaluate potential relationships between the greenness of areas surrounding public elementary schools and student performance on standardized tests in Math and English as a measure of academic performance. The authors analyzed Composite Performance Index (CPI) data from 3rd graders at 905 Massachusetts, USA public schools covering the period 2006–2012 in relation to estimated greenness in spring (March), summer (July) and fall (October). Their analysis showed a highly significant association between greenness around schools and academic achievement in March (approximately the time that testing occurred) but not in October when greenness would likely have been less apparent. The positive association persisted regardless of gender or economic status. This study is included with diseases, since education attainment is often a major predictor of socio-economic status which, in turn, is regularly associated with better or worse health (Winkleby et al., 1992).

Overall, these results demonstrate that there is a great deal of evidence suggesting that there are many, varied health and well-being benefits of human exposure to nature or more natural, green settings.

3.3. Human health and biodiversity

Bernstein (2014),and references therein, nicely summarized literature on the case for biodiversity as support for food, natural products and drug discovery. Hough (2014) focused on studies dealing with the human health effects of loss of biodiversity, including changes in ecosystem function, disease regulation, and direct and indirect exposure to biodiverse environments. Both of these reviewers and Rook (2013) examined some of the important roles of human gut microbial diversity in human health, and how environmental effects on the gut microflora may contribute to health problems including obesity, asthma, some forms of bowel disease, and other inflammatory disorders. Here we explored three potential mechanisms by which biodiversity may impact human health: psychological and physical health parameters, chronic allergy and inflammatory diseases, and transmission of infectious disease.

3.3.1. Psychological and physiological benefits of biodiversity

While the evidence for direct linkages between health outcomes and human exposure to biodiversity remains quite limited, there is mounting evidence that not just exposure to nature, but contact with diverse natural habitats and many different species, has important positive impacts for human health. In a seminal study, Fuller et al. (2007) determined that the psychological and physical benefits of contact with nature increased with species richness and habitat diversity. In this study, conducted in green space in a small United Kingdom city, health and well-being indicators measured included the ability to think and gain perspective (“reflection”), the degree of feeling unique through association with a particular place (“distinct identity”) and the degree to which one's sense of identity is linked to green space through time (“continuity with past”). All these benefits significantly improved with increases in species richness (taxon density and heterogeneity) of plants, and were also positively related to bird richness, although no association was found with butterfly diversity. Perceptions of species richness were also examined, and corresponded with sampled species richness for plants and birds. The diversity of habitats (up to 7), and plant and bird variety in a green space were also positively correlated with at least one measure of psychological well-being. The authors reported that causality in this study was not clear, but suggested that the results for plant species diversity in particular “hint that gross structural habitat heterogeneity might cue the perceptions and benefits of biodiversity. If this is the case, management may enhance biodiversity levels, ecosystem service provision and the well-being of the human urban population” (Fuller et al., 2007).

A few studies have dealt with aquatic exposures. In a preliminary analysis based on aquarium viewing with fewer or more species, Cracknell (2013) determined that when people watched aquariums with different levels of diversity of fish for 10 min, the more species-rich aquariums led to greater decreases in people's heart rates as well as to bigger improvements in their self-reported moods. These preliminary results suggest that fish biodiversity positively impacted both the physical measurements and perceived sensations of health. This was the only study we found that considered specific health effects of aquatic/marine biodiversity and one of the few that considered living organisms beyond terrestrial vegetation. However, Wyles et al. (2013) referenced numerous studies that have addressed recreational, educational, and relaxation values of visiting zoos and aquaria, as well as potential for changes in visitor attitudes and behaviors. Similarly, White et al. (2010) utilized inanimate photographs to assess study subjects' preferences for different more or less natural environments that did or did not include water. Studies that employ photographs or videos of biodiverse environments and/or that make greater use of aquaria, zoos, and museums might provide important additional insights regarding health effects of biodiversity exposure.

Esthetic appreciation of biodiversity may contribute to the cultural and emotional components of human well-being. Lindemann-Matthies et al. (2010) conducted field studies and experiments in Switzerland to evaluate the effects of plant species diversity on people's esthetic appreciation for grasslands that included both forbs and grasses. They found that people were able to differentiate between species-rich and species-poor assemblages, although they typically overestimated low and underestimated high diversity, and that diversity increased esthetic appreciation for the plant communities. Dallimer et al. (2012) found that even perceived biodiversity can relate to an increased sense of psychological well-being. They determined that study participants were not very good at assessing the actual level of species richness of plants, butterflies, and birds, but as their perceived sense of the level of biodiversity increased, their assessment of their well-being rose.

Some exposure to wildlife also may provide health benefits. In a review dealing principally with health impacts related to low levels of physical activity, Bird (2004) not only covered some of the literature illustrating the connection between physical activity in nature and improved health but specifically noted the value of, and preference for, wildlife-rich (i.e., biodiverse) green spaces. Similarly, Wyles et al. (2014) conducted one of the few studies that have concentrated on marine coastal features and found that wildlife watching was among the top factors in improving visitors' mood and happiness. While these studies did not address overall biodiversity, they demonstrated that some components of biodiversity (e.g., charismatic megafauna) are tied to well-being. Not surprisingly, these were the components that tend to be of interest to the public at large.

Although the evidence is limited to date, taken together these studies suggest that contact with biodiverse environments, or those perceived to be biodiverse, result in positive benefits to human well-being.

3.3.2. *Biodiversity and chronic allergies and inflammatory diseases*

Rapid declines in global biodiversity may be contributing to another megatrend in human health and well-being, the increasing prevalence of allergies, asthma, and other chronic inflammatory diseases especially among urban populations (Hanski et al., 2012). A number of studies have determined that human exposure to diverse natural habitats is critical for development of normal human immune responses to allergens and other disease-causing factors [e.g., see (Haahtela et al., 2013; Hanski et al., 2012; Rook, 2010) in addition to papers cited by Bernstein (2014) and Hough (2014)]. Evidence from these studies suggest that allergy may result from a *lack* of exposure to microbes, especially in early childhood, which results in the human microbial community getting "poor training" which leads to hyper-responsiveness to bioparticles (allergy) (Haahtela et al., 2013). Microbe-rich environments confer protection against allergic and autoimmune diseases, particularly among young children (Lynch et al., 2014). Humans have evolved to deal with microbes in the environment such that protective mechanisms against inflammatory diseases involve the activation of innate and regulatory networks by continuous exposure to microbes on the skin and in the gut and respiratory tract; these microbes induce immune regulatory circuits in the human body. Thus, it is likely that decreases in environmental biodiversity may in part be responsible for some human immune dysfunction (Haahtela et al., 2013). This phenomenon has been called the "biodiversity," "Old Friends," or "hygiene" hypothesis (Hanski et al., 2012).

Basically, the biodiversity hypothesis posits that healthy development of the microbiota of human skin and gut depends in part on inoculation with microbes from environmental sources. The hypothesis has been amplified to suggest that the ongoing and rapidly increasing global loss of macrodiversity (habitat and species richness of macroorganisms and their associated microbial biodiversity) is leading to a decrease in human exposures to microbial diversity, which in turn may affect the human microbiota in ways that result in a wide variety of inflammatory-based illnesses (Haahtela et al., 2013). These disorders include allergies and asthma, inflammatory bowel disease (IBD), cardiovascular disease (CVD), some cancers, potentially some neurodegenerative diseases, type 2 diabetes, inflammatory-associated depression, and some presentations of obesity (Rook, 2013, 2010).

In addition to the global megatrend data, results from regionally specific and mechanistic studies support the biodiversity hypothesis. Hanski et al. (2012) demonstrated that the environmental biodiversity around the homes of adolescents influenced the composition of bacterial classes on the individuals' skins. Compared with healthy individuals, those who had allergies had lower environmental diversity around their homes and also lower diversity of Gram-negative gammaproteobacteria on their skin. While the authors were not able to isolate a specific mechanism for the environmental influence on allergic hypersensitivity, they did report suggestive evidence for an important potential regulatory role for *Acinetobacter* species which is supported by results from other studies. For example, Fyhrquist et al. (2014) studied bacteria associated with reduced levels of allergic responses. They identified over 1000 bacteria from forearm skin of 118 study participants and determined that *Acinetobacter* spp. on the skin were strongly associated with expression of anti-inflammatory genes in blood cells of healthy subjects but not in those with atopy (a predisposition to allergic responses including asthma). In laboratory studies, they found that the *Acinetobacter* spp. induced production of anti-inflammatory and T_H-polarized immune responses that helped balance the immune system and thus provide protection against development of atopy. Debarry et al. (2007) demonstrated that specific strains of the bacteria *Acinetobacter lwoffii* and *Lactococcus lactis* from cowsheds provided allergy protection for children and determined that the mechanism of action likely involved promotion of an immune deviation from T_H2 to T_H1 cells rather than by stimulating activity of regulatory T cells. Later, Debarry et al. (2010) determined that a lipopolysaccharide produced by *A.*

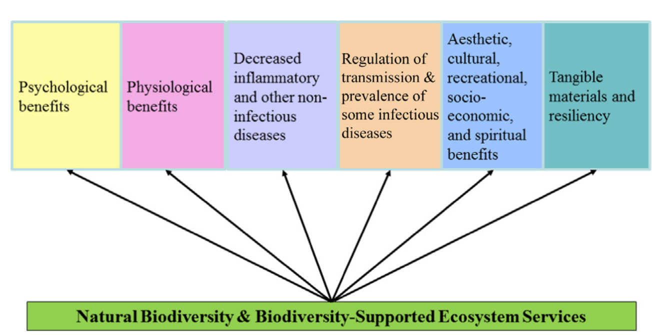

Fig. 1. Major pathways through which biodiversity may provide health and well-being benefits to humans.

lwoffii mediated the effects. Ege et al. (2011) used data from two large studies of children in southern Germany and Bavaria and determined that children raised on farms were less likely to have asthma than those reared in non-farm conditions in the same rural areas. Based on dust samples from the children's homes, they identified the likely causative agents as the higher levels of exposure to environmental bacteria and fungi among children raised on farms. Ege et al. (2011) were not able to determine which specific microorganisms provided asthma protection, but speculated on two possible mechanisms by which the protective microbes might work: (1) by inducing regulatory T cells that may modulate balance of T helper cells associated with asthma, or (2) preventing harmful bacteria from colonizing the children's lower airways.

Exposure to other specific types of bacteria may also be important for proper immune function. For example, Lynch et al. (2014) utilized data from the Urban Environment and Early Childhood Asthma (URECA) study that involved a cohort of 560 high-risk children in Baltimore, Boston, New York, and St. Louis and a subgroup of 104 children for whom house dust was collected during life year one. This was the first large study to consider children's exposure to both allergens and microbial diversity during the critical first-year period of life. They found that first-year exposure of children to higher bacterial biodiversity and to specific bacteria (Firmicutes and Bacteriodetes) was negatively associated with the development of allergic reactions, including wheezing, by age three. Particularly interesting and important are their findings that children with highest exposures to both allergens and putatively protective bacteria during the first year of life exhibited neither wheeze nor atopy at age three, while children with atopy alone had exposures to allergens but not the putatively protective bacteria during year one. Lynch et al. (2014) also noted that most of the bacteria that appeared to be protective belonged to the families Prevotellaceae, Lachnospiraceae, and Ruminococcaceae, all of which include species known to colonize humans and to produce immunomodulatory metabolites.

The biodiversity hypothesis is also supported by studies on the gut microbiome, specifically regarding intestinal diseases such as IBD, for which no infectious causative agent has been identified (Round and Mazmanian, 2009). A considerable amount of this information has been reviewed by Bernstein (2014) and Hough (2014) and will not be repeated here, but at least two additional papers deserve discussion. In their review, Round and Mazmanian (2009) discussed in detail the concept of dysbiosis, that is, alterations of the human microbiome that result in changes to the immune system leading to inflammatory-based illnesses such as IBD. They cited earlier work by Mazmanian and colleagues that had demonstrated that a particular molecule, polysaccharide A (PSA), produced by the symbiotic bacterium *Bacteroides fragilis*, stimulated healthful immune responses. Round and Mazmanian (2010) conducted elegant laboratory experiments to investigate how balance between the opposing pro- and anti-inflammatory arms of the human immune system might be affected by gut microbiota. They extended the previous findings regarding the role of PSA from *B. fragilis* in protecting against intestinal inflammation and reported that PSA induces production of certain regulatory T-cells that suppress other pro-inflammatory T-cells, thereby identifying a possible mechanism of action.

Placed into context with other evidence [e.g., see discussion above and (Bernstein, 2014; Hough, 2014; Rook, 2013)], it is clear that environmental microbiological diversity may profoundly affect the human microbiome and through those effects influence the operation of the human immune system. Thus, there appears to be a potentially powerful association between the diversity of habitats experienced, the diversity of microbiota on and in the human system, and certain health outcomes. In this area, considerable progress is being made in elucidating at least some of the potential molecular mechanisms by which different microbiota may influence the occurrence of human inflammatory disorders.

3.3.3. Disease transmission in biodiverse landscapes

Numerous authors have postulated that biodiversity may affect the emergence and transmission of infectious diseases, especially vector-borne diseases. Most of these studies are based on the premise that species and habitat diversity can affect the transmission of diseases in a number of ways, such as by altering the abundance of the host or vector (the "dilution effect"); changing the behavior of the host, vector, or parasite; or influencing the condition of the host or vector (Keesing et al., 2010). Recent investigations, particularly in terrestrial systems, suggest that transmission rates of certain pathogens may decrease when the diversity, not just the density, of available hosts (i.e., host biodiversity) increases (Pongsiri et al., 2009). Likewise, loss of predators may increase host or vector populations, increasing the prevalence of pathogens and risk for human transmission (Pongsiri and Roman, 2007). Based on a modeling study, Laporta et al. (2013) proposed that greater abundance and diversity of warm-blooded mammals might decrease the likelihood of malaria outbreaks in tropical forests. An exclosure study in the African savannah suggested that the loss of diversity of large herbivores in that ecosystem could lead to elevated risk of transmission of *Bartonella* spp, the bacterial parasite responsible for bartonellosis (Young et al., 2014). This effect apparently was due to an increase in the rodent population with a resultant increase in fleas which are the vector for *Bartonella*. Young et al. (2014) submitted that the mechanisms for this increase may have been a decrease in competition between the large herbivores (mainly giraffe, zebra, elephant and gazelle) and the rodents, as well as the indirect effect of changes in the vegetation structure with the loss of the large herbivore species. Their findings suggest that examining only the per capita prevalence of a disease may not be the best metric for identifying human disease transmission risks, and that susceptible host regulation may be an underrepresented ecological function of intact, biodiverse ecosystems.

In another example, Derne et al. (2011) examined a possible relationship between incidence of human leptospirosis in 19 island nations (where the potential host, rats, may have large populations) and island biodiversity. Annual leptospirosis incidence rates (adjusted for socioeconomics and latitude) were significantly negatively associated with both total species counts and terrestrial mammalian counts. Furthermore, terrestrial mammalian species richness was the biodiversity component shown to have the strongest association with leptospirosis incidence. The authors stated: "Leptospirosis incidence rates varied dramatically with small changes in terrestrial mammalian species numbers when mammalian species richness was low. As terrestrial mammalian species richness increased, the decrease in leptospirosis incidence with each additional mammal species became progressively smaller." The authors remarked that these results did not demonstrate a causal relationship and required further investigation but were suggestive that biodiversity has a "bioregulatory effect" on the transmission of leptospirosis, and thus incidence, through the dilution effect and/or predatory and competitive interactions (Derne et al., 2011). Importantly, aquatic and marine mammals were not considered in the study, but a wide variety of marine mammals may become infected with leptospirosis and may be a growing source of human exposure in areas where there are large and diverse populations of marine and domestic terrestrial mammals and heavy human activity (Cameron et al., 2008). It will be important to determine what, if any, role the diversity of marine mammals may play in incidence and transmission of leptospirosis.

At a global level, emerging infectious disease (EID) events are increasing (Jones et al., 2008), and EIDs not only affect humans but also the health of other organisms and their ecosystem functions (Crowl et al., 2008; Plowright et al., 2008). The spread of invasive species, disease vectors, and pathogens alters diversity, functions and services of ecosystems. In at least some cases, diverse ecosystems are believed to ameliorate disease transmission, promoting ecosystem health. For example, Raymundo et al. (2009) demonstrated linkages between trophic functional diversity and disease in corals. A survey of 14 reef sites across the central Philippines showed that the taxonomic diversity of reef fish, which are a “dominant structuring force” on abundance and distribution of other taxa on coral reefs, is significantly negatively correlated with coral disease prevalence. Their results were consistent with relationships between fish diversity and the presence of coral disease in studies from the Great Barrier Reef. Raymundo et al. (2009) suggested that high fish diversity plays an important role in limiting disease in coral reefs through ecological control of vector species; corallivorous butterfly fishes, in particular, are vectors of coral diseases. Similarly, in an elegant study combining field observations, laboratory and mesocosm experiments, Johnson et al. (2013) demonstrated an approximately 50% reduction in transmission of the virulent amphibian pathogen, *Ribeiroia ondatrae,* with increasing amphibian species richness. They concluded that “preserving functional diversity – including genetic diversity and community richness – has the potential to ameliorate pathogen transmission and offer a novel, cost-effective approach to disease management.”

The above examples notwithstanding, Keesing et al. (2006) concluded that there was no simple, clear-cut answer as to whether biodiversity might increase or decrease risk of infectious disease in humans. While the weight of available evidence tended to favor the general idea that higher diversity reduces disease risk, they noted much variability among individual diseases and situations. Ostfeld and Keesing (2012) conducted an extensive review of literature related to the “dilution effect,” defined by Keesing et al. (2006) as “the inverse relationship between diversity and disease risk.” They considered both whether the dilution effect could occur and if so, whether it occurs in nature. They concluded that the dilution effect both could and does occur, and it is likely common in a wide variety of diseases. As a result, they recommended consideration of mitigation of human-caused reductions in host diversity.

In contrast, in a meta-analysis of 16 biodiversity-disease relationships, including eight dealing with hantaviruses, three with West Nile, two with Lyme disease, and three with other diseases, Salkeld et al. (2013) determined that there was little support for a general conclusion that biodiversity decreases zoonotic disease risk. Salkeld et al. (2013) stated: “Our meta-analysis…provides very weak support, at best, for the dilution effect, and by extension the assertion that the preservation of endemic biodiversity will reduce the prevalence of zoonotic diseases.” They posited that the relationship between biodiversity and zoonotic disease is likely idiosyncratic, and that understanding the specific ecological factors controlling dynamics of a given disease in a particular geography was much more important. A very recent and extensive review by Wood et al. (2014) also concluded that the relationship between biodiversity and infectious disease is complex, and they hypothesized that the conditions needed for the dilution effect were unlikely to be met for most important human diseases. Moreover, they concluded that it is important to consider more than one disease at a time when examining the role of biodiversity on disease control and very few studies have done so to date. Wood et al. (2014) recommended that research should prioritize assessing the shape and direction of the biodiversity-disease relationship across a diverse sample of diseases in order to ascertain if there are certain conditions or ecological communities that are more likely to produce the dilution effect.

Considering all these results, we believe the best current answer to the question of whether increased biodiversity reduces risk from infectious diseases is “probably not, but it depends.” This question requires further research about the mechanisms and effects of biodiversity on disease transmission, perhaps on a case-by-cases basis (e.g., for malaria and Lyme disease). It is also important to note that some of the research on biodiversity and disease is really more about habitat destruction and subsequent loss of biodiversity. It may be that a more important question is to examine the relationship between habitat disturbance or loss and disease incidence without focusing specifically on biodiversity as a mechanism. This would allow the testing of other hypotheses for why diseases are spreading such as human modification of habitats that may facilitate transmission of human pathogens, stress causing reduced immune function, or the fostering of commensal species that have parasites evolved for humans (Young, 2014). In addition to the need for more research on those specific situations where biodiversity may play a key role in reducing transmission of certain infectious diseases, continuing to take a precautionary approach focused on stronger biodiversity conservation would have overall positive effects on human well-being.

4. Discussion

It is now well-established that biodiversity supports critical ecosystem services for people, such as food and raw materials, that support lives and livelihoods (MA (Millennium Assessment), 2005; Loreau and de Mazancourt, 2013; Balvanera et al., 2006; Cardinale et al., 2006; Naeem et al., 1994). The ability of ecosystems to provide sufficient ecosystem services to humans not only support basic human needs, but also “has an important protective function for human mental health” (Dean et al., 2011) including a sense of security (Diaz et al., 2006). A central theme of much research in biodiversity and ecosystem services is the necessity to “conserve biodiversity to improve human well-being” (Naeem et al., 2012). Sandifer and Sutton-Grier (2014), Chivian and Bernstein (2008), Bernstein (2014) and Hough (2014) have summarized many other positive effects of biodiversity on the human condition. Our exploration of literature from the ecological and environmental sciences, and from policy, planning, public health, and biomedical fields extends the previous body of work and demonstrates that biodiversity provides many additional benefits to human health via a variety of pathways beyond its oft-cited roles in the provisioning of food and raw materials to support human life (Fig. 1). And yet, perhaps more than anything, this review highlights the paucity of existing data from critical examinations of relationships between specific human health parameters, nature, and biodiversity.

To date, a wide range of positive mental and emotional effects have been found to be associated with human exposure to nature as summarized here. Much less work has focused on physical health, but the evidence indicates positive impacts of nature exposure on general health, stress reduction, increased physical activity, and reduced incidence/levels of cardiovascular, intestinal, and respiratory diseases including COPD, asthma, allergies, inflammatory disorders, and a host of other maladies (Table 1). However, while most of the studies report some types of quantitative information, relatively few include robust data sets on the actual prevalence of disease in relation to nature exposure, and even fewer provide information relating exposure to causality of observed or reported health effects.

This vast volume of literature also includes tantalizing hints that exposure to biodiverse surroundings, or even to nature just perceived to be biodiverse, may impart direct health benefits to humans. But, the number of studies that directly measure specific human health benefits from exposure to biodiverse environments is small. Some of the results, particularly regarding influence on regulation of infectious diseases, are sufficiently variable to lead to conclusions that, while there may be discernible effects for a relatively small number of diseases, there is no generally applicable relationship.

Given the volume of literature, it is particularly disappointing that so few studies do a thorough job of analyzing human health metrics in response to nature or biodiversity. This is especially true for psychological studies, many of which lack adequate controls (such as additional relaxation controls besides experiencing natural settings) and follow-up and are based on small sample sizes and short-term exposures. In their review of urban green space–health connections, Jorgensen and Gobster (2010) found 18 studies that mentioned biodiversity. However, only one of these, Fuller et al. (2007), addressed psychological health directly, and none they reviewed reported physical health measures. Here, we summarized a few other biodiversity-related studies from the literature, but many crucial questions remain, such as What is it about experiencing nature – and biodiversity – that is calming, restorative, and health-protective? What are the actual mechanisms by which nature exposure affects health outcomes, particularly beyond microbial influences on the immune system? What roles does biodiversity per se play, and how can these best be identified, understood, and measured? Might the structural heterogeneity of diverse habitats be involved, as speculated by Fuller et al. (2007)?

More robust analyses of relationships between human health, nature, and biodiversity remain as key gaps in ecological and medical research, especially regarding mechanisms of causation. Sufficient observational and correlational evidence now exists to support the basic premise of a wide range of health benefits, but for the most part how these benefits are mediated remains unknown.

The only unambiguous causal relationship demonstrated between environmental biodiversity and human health is that relating to the maintenance of a healthy immune system and reduction of inflammatory-based diseases (Bernstein, 2014; Hough, 2014; Rook, 2013). In his seminal paper, Rook (2013) concluded that "…the requirement for microbial input from the environment to drive immunoregulation is a major component of the beneficial effect of green space, and a neglected ecosystem service that is essential for our well-being." He also pointed out that modern agricultural and building practices, along with urban lifestyles, have reduced opportunities for many people to be exposed to a broad range of environmental microbial biodiversity. Unfortunately, with the exception of a relatively few studies dealing with allergic diseases, knowledge of what may constitute a healthful environmental microbial exposure is extremely limited [e.g., see (Lynch et al., 2014; Debarry et al., 2007; Ege et al., 2011; Fyhrquist et al., 2014)]. How environmental microbial biodiversity from a broad range of environments, including the ocean and coasts, might be important to healthy immune systems or play other causative roles in human and animal health, and what specific characteristics of the microbial biota of different environments provide human health benefits are vitally important areas for further research.

In addition, the marine environment, its ecosystem services, and biodiversity are in particular need of attention from the standpoint of values to human health and well-being, beyond the provision of food, recreation, and jobs. While several studies show positive health results from exposures to nature featuring water (White et al., 2010; Laumann et al., 2003; Felsten, 2009) and coasts (White et al., 2013; Coon et al., 2011; Wyles et al., 2014; Wheeler et al., 2012; Pretty et al., 2011; Fortescue Fox and Lloyd, 1938; Bauman et al., 1999), these papers incorporated little if any information regarding the biological characteristics of these environments and any potential relationship of those traits to health effects. Thus, we do not know what about these ecosystems led to the positive human health effects. We found no studies that carefully evaluated any potential human health effects of marine biodiversity, beyond recreation (Schuhmann et al., 2013) and provisioning services (e.g., food, pharmaceuticals, other products). Nevertheless, marine ecosystem and species biodiversity may have important impacts on the amount or type of human health benefits that result from exposure to coastal and marine environments. For example, do people derive more relaxation or pleasure from experiencing several coastal habitats (such as beach and salt marsh) versus just one habitat, or does exposure to marine species richness, such as may be observed in a coastal mangrove forest or a coral reef, have measurable health benefits? Might coastal and marine environments provide important microbial exposures, as implied by Rook (2013)? For the marine environment, biodiversity has been suggested as a "common currency" (Palumbi et al., 2009; Foley et al., 2010) or "master variable" (Duffy et al., 2013) for evaluating ecosystem health and conducting evaluations and trade-off analyses. It might serve a similar function in assessments of the relative healthiness of various environments for humans.

4.1. Additional recommendations for research priorities

A fundamental question is how best to measure biodiversity in order to define human exposure. Is species richness the best metric, or should researchers examine functional trait or genetic diversity? The ecological literature suggests that functional diversity is a, and perhaps the, key factor in sustained delivery of biodiversity-supported ecosystem services. How should this functional diversity be measured in studies concerning biodiversity contributions to both ecosystem [sensu (Tett et al., 2013)] and human health [e.g., see (Pereira et al., 2013b)]? The recently proposed Global Biodiversity Observation Network (Scholes et al., 2008) and the U.S. Marine Biodiversity Observing Network (Duffy et al., 2013) could help to integrate and routinize collection of biodiversity data and information. This information could serve as a foundation for design of experiments that would provide robust biodiversity exposures so that potential effects on specific psychological and physical health parameters could be tested, and dose-response, duration of effect, and potential mechanisms of action identified.

In order to demonstrate whether biodiversity per se or even the perception of biodiversity can improve mental and physical health, research is needed on the quality of green space, (for example measuring species richness as a potential quality indicator), the microbial diversity associated with different environments, and the associated health benefits [e.g., (Keniger et al., 2013; Fuller et al., 2007)]. Also needed are well-designed epidemiological investigations that use carefully-selected health and biodiversity indicators to begin to tease apart potential causal relationships between biodiversity and human health factors (Dean et al., 2011), establish extent and duration of effects (e.g., long-term vs. transitory), and determine whether multiple short-term exposures may sustain, increase, or decrease one or more health outcomes. Much more data on biodiversity effects on a broader range of physiological health parameters and epidemiological studies that look at specific diseases in greater detail will be necessary. Systematic and sustainable approaches to observing and monitoring biodiversity across different levels (genes, species, habitats, ecosystems), in both terrestrial and aquatic domains are also required. Currently, relatively little biodiversity monitoring is integrated or accessible in ways that make it useful to public health or sometimes even natural resource management communities. Due to the complexity of the types of questions and hypotheses that multi-disciplinary biomedical-ecological research will entail, virtually all of these efforts will require much more collaborative research where ecologists, landscape and environmental scientists engage with biomedical scientists, public health specialists, and social scientists (Sandifer and Sutton-Grier, 2014; Frumkin, 2002).

On the human side, which human health metrics are likely to be most useful and relevant indicators of the impacts of nature/biodiversity on human health? Numerous studies cited here have focused primarily on self-reporting of psychological benefits or on a few easy-to-measure physiological parameters such as heart rate, usually recorded during short-term exposure studies. These indicators provide some evidence of the positive benefits of nature and biodiversity on human well-being, but other parameters likely would provide both more nuanced and definitive information about whether biodiversity or perceived biodiversity affects human health. Several longer-term, large cohort epidemiological studies are cited here [e.g., see (Lynch et al., 2014; Maas et al., 2009a; Villeneuve et al., 2012; Lachowycz and Jones, 2014; Wilker et al., 2014; Hanski et al., 2012; Ege et al., 2011; Hystad et al., 2014; Mitchell and Popham, 2008)], but much more of this type of work is needed as well, and with a stronger focus towards questions of likely causality and long-term health benefits. At the same time, whether repeated short-term exposures to nature or biodiversity might be effective in reducing event- or disease-associated anxiety and stress should be evaluated as well.

There are also critical needs for the collection of health data at large scales and over long periods of time, and particularly for researchers to be able to access and utilize such data. For example, the work by Maas et al. (2009a) demonstrated the research value of electronic medical records, especially where they are available essentially for entire populations as in the Netherlands. As a result, they were able to identify reduced incidences of particular diseases or disease types with exposure to green space. Similarly, because Hanski et al. (2012) had data from entire communities and stretching over many years, they were able to determine that the amount of diverse habitats around a child's home impacted the diversity of microbes on skin and hence the level of allergic sensitization. These types of analyses are only possible when large-scale, long-term health records are available to researchers. Use of these types of data means resolving issues related to data handling, storage, and access in order to respect and protect privacy. Thus, there is an urgent need for scientists from multiple disciplines to work with legal and health policy experts to determine how best to make available as much actual health data as possible to bona fide researchers [IOM (Institute of Medicine), in press].

More detailed studies concentrating on a few high-prevalence, major-effect diseases might help to determine strength and persistence of health effects, develop a foundation for testable hypotheses regarding mechanisms of action, and drive policy to improve both health and conservation of biodiversity. For example, CVD is the number one cause of death in the U.S. Yang et al. (2012) as well as globally [(WHO, 2013), Factsheet [317]]. Yang et al. (2012) listed seven health metrics for CVD: not smoking, physical activity, normal blood pressure, normal blood glucose level, normal total cholesterol concentration, normal weight, and healthy diet. Of these, blood pressure can be measured quickly and without any invasive process, and reducing occurrence of hypertension would likely decrease mortality due to CVD (Yang et al., 2012). Reduced blood pressure in response to nature exposure was found in several studies, but not all where it was measured (Table 1). Minimally invasive procedures could be used to collect saliva swabs (e.g., for cortisol and perhaps other analyses), glucose and cholesterol levels could be determined from a single blood sample, and urine samples could be used to detect diabetes, kidney and liver disease, urinary tract infections, and levels of certain hormones. Collection of saliva, blood or urine samples would require more stringent research controls and permissions than would blood pressure. In addition to studies of physiological response, future research should also include much more robust examination of psychological factors, and especially address esthetic, cultural, recreational, and spiritual ecosystem services and their potential links to biodiversity. Greater involvement of the public health community is needed to identify the kinds of meaningful health data that could be collected with the least difficulty and for participation in collection of health data in studies related to beneficial effects of nature and biodiversity. The ongoing revolution in digital and tele-connected mobile and wearable sensors for a variety of health, activity, and exposure metrics is likely to offer amazing new opportunities to collect a wealth of health-relevant data in relation to environmental exposures of many kinds.

4.2. Policy and planning implications

Much recent literature discusses the need to “green” urban areas so as to enhance human health and well-being [e.g., (Brown and Grant, 2005; Barton, 2005; Barton and Grant, 2006; Barton et al., 2009)], but as yet the potential for using nature as a mechanism to improve human health has not been emphasized widely in broad health policies. One important recent exception is the adoption of a policy entitled “Improving Health and Wellness through Access to Nature” by the American Public Health Association (APHA) (Sullivan et al., 2014). Many attempts to justify support for conserving natural areas and biodiversity rely predominantly on either ecosystem service values to humans (e.g., food, jobs, medicine) or biodiversity's intrinsic worth (Cardinale et al., 2012; Naeem et al., 2012). There are relatively few examples in ecosystem and biodiversity science or even in urban ecology where humans are treated as major functional components of ecosystems (Mace et al., 2012; Norris, 2012; Barton, 2005; Armsworth et al., 2007). Yet, the growing evidence summarized here suggests that the contributions of biological complexity to human health and well-being are important and could be used as a strong and potentially persuasive argument for protecting and restoring ecosystems and biodiversity. Enlisting the public health community to support biodiversity conservation might be an excellent way to gain broader public interest and acceptance of expanded conservation actions that also would enhance public health. Having ecologists join with the APHA in further elaboration and implementation of its new policy might be a useful early step.

Despite the limited information about specific mechanisms by which nature and biodiversity may support human health and well-being, protecting and restoring a diversity of natural habitats, as well as managing and increasing green space and biodiversity in urban environments, are essential for maintenance of human health and well-being in an urbanizing world (Brown and Grant, 2005). Improving human health is a powerful motivator for addressing planning issues and for drawing support from multiple constituencies (Barton et al., 2009). Unfortunately, modern city planning has tended to focus on low-density, car-dependent communities with associated reductions in physical activity such as walking. This situation, combined with other factors such as vastly increased amounts of time spent in indoor work and recreational pursuits using electronic media, has resulted in unhealthy, sedentary lifestyles that are contributing to some of the primary diseases facing the world today, including obesity, heart disease, and depression. As an alternative, Barton et al. (2009) described ideal components of a health-integrated planning system for cities to which should be added monitoring of results of new planning decisions on human health and making adaptive changes as needed, similar to the concept of adaptive management in ecology (Holling, 1978). More recently Steiner (2014) included the application of an ecosystem services approach among his four frontiers of urban design and planning and embraced the concept of urban ecological design that contributes to human health. If adopted broadly, changes in urban environments to promote human exposure to biodiverse nature might help lessen some of the negative health effects of modern lifestyles. However, planners, ecologists, and public health experts must also consider potential collateral damage from urban modifications that have the intent of improving green space and its associated health benefits in deprived areas that may then result in environmental justice problems related to gentrification and displacement of the very populations the project was designed to benefit (Wolch et al., 2014).

Fundamental changes are needed to place human health and well-being as the *central purpose* of urban planning (Barton et al., 2009) and at a broader scale in ecosystem-services approaches to decision-making (Sandifer and Sutton-Grier, 2014). The WHO's global Healthy Cities (www.who.int.healthy_settings/types.cities/en/) and Healthy Urban Planning initiatives provide some important opportunities for progress. Such initiatives may provide useful models for development of policies linking biodiversity conservation, human health, and land, coastal, urban, and public health planning policies and activities. Resulting efforts to provide greater quantity, quality, and diversity of green spaces for human and wildlife use, and joint efforts among conservation groups, public health entities, neighborhood associations, environmental justice leaders, and local planning authorities, including those dealing with the marine environment, could lead to very different, healthier urban landscapes and coastlines (Brown and Grant, 2005). As an example, following Hurricane Sandy there has been a resurgence of interest in the U.S. in restoring or creating more natural coastal infrastructure (i.e., healthy ecosystems such as oyster reefs, salt marsh, dunes, and mangroves) that help protect coastal areas from storms and other extreme events. This is one of the main components of the Rebuilding Strategy assembled by President Obama's *Hurricane Sandy Rebuilding Task Force* (Hurricane Sandy Rebuilding Task Force, 2013). Similarly, Arkema et al. (2013) determined that if the U.S. could conserve its existing coastal habitats, it could significantly reduce exposure of vulnerable people and property to storms and other natural hazards. There is also a growing interest in using more "green" (natural) infrastructure (including storm water wetlands, rain gardens, and green roofs) in cities to improve water quality and quantity, protect against flooding, provide localized cooling, and promote socio-economic as well as psychological and physical human health benefits (Tzoulas et al., 2007).

5. Conclusions

We are just beginning to appreciate the breadth of human health benefits of experiencing nature and biodiversity, and more research examining these linkages is absolutely critical. Nevertheless, based on the limited evidence available to date, science and policy efforts focused on understanding nature-biodiversity-ecosystem service-health linkages and incorporating more natural areas and biodiversity in the design and protection of our cities and coastal communities are likely to enhance ecosystem, community, and human resilience. To achieve this goal we need (1) a much more in-depth research focus on potential health effects of experiencing nature and biodiversity, including coastal and marine biodiversity, with emphases on quantification of health outcomes and mechanisms of causation of observed effects; (2) a re-envisioning of urban, land-use, and marine spatial planning that places human health and well-being at the center, facilitates human interaction with nature (e.g., green space) to the fullest extent possible, and ensures people are surrounded by and have access to biologically diverse natural habitats; (3) a new coalition of ecologists, biomedical and public health scientists and practitioners, land-use/urban planners, and social scientists to focus on development and implementation of policies that promote human interaction with biodiverse environments and strongly support conservation and restoration of biodiversity; and (4) broad-scale studies to more fully investigate the potential roles that environmental microbial biodiversity may play in many different health contexts. We are at a key juncture in human history where biodiversity loss is occurring daily and accelerating in the face of a burgeoning and increasingly affluent human population, ongoing climate change, and rampant development and habitat degradation/destruction. The science and policy opportunities laid out here provide a win for human health and for biodiversity conservation.

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