Towards a unified understanding of human-nature interactions

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Preface

Interest in the direct interactions between individual people and nature has grown rapidly. This attention encompasses multiple academic disciplines and practical perspectives. A central challenge thus lies in creating a rich cross-disciplinary understanding of these interactions rather than one that might become characterised by little conceptual, terminological and methodological unity. Here, to facilitate the former outcome, we bring together concepts and theories about direct human-nature interactions drawn from across diverse disciplines within a unified conceptual framework. Using this framework, we discuss the linkages among key concepts and theories, identify important knowledge gaps, and suggest directions for future research.

The past decade has seen an explosion of interest in the direct interactions between individual people and nature (hereafter 'human-nature interactions'). This interest has spanned a range of academic disciplines, including ecology (***1–3***), conservation science (***4, 5***), public health (***6–10***), immunology (***11, 12***), urban planning (***13***), leisure (***14***), psychology (***15***), and education (***16***). It has also manifested in the development of policy and practice (e.g., ***17***). The reasons, some linked, for this increased attention are arguably fourfold. First, it reflects growing recognition of the human health benefits of direct interactions with nature (***6, 8–12***), and in interventions by which these benefits might be enhanced (***17***). Second, there has been increased concern about widespread loss of positive direct interactions of people with nature, particularly that associated with urbanisation, and the consequences this may have for their attitudes and behaviour towards nature (***5***). Third, there has been a recent rise in the occurrence of some negative direct interactions with nature (e.g., attacks by large vertebrates) (***18, 19***), perhaps in part because of a decline in people's knowledge of how to behave appropriately. Finally, there has been a broad shift in conservation science and policy towards a 'people and nature' paradigm of two-way, dynamic relations (***4***).

The diversity of academic and non-academic contexts in which recent growth of interest in direct human-nature interactions has occurred poses both challenges and opportunities. The challenges include the potential for the development of different terminologies, conceptualisations and approaches to addressing the same or closely related issues. The opportunities include the potential for a far richer cross-disciplinary understanding to be quickly developed around a topic that so many would seem to agree is of fundamental significance in the face of a biodiversity crisis (e.g., ***5, 20***). To encourage development of these opportunities, here we bring together concepts and theories related to direct human-nature interactions within the context of a unified conceptual framework. In so doing we provide a common terminology for these concepts and theories (used in a broad sense to include any set of testable ideas, hypotheses and assumptions with more or less empirical support), discuss their linkages, identify important knowledge gaps, and suggest key directions for future research. Although many conceptual frameworks have previously been developed to deepen understanding of human-nature interactions, most of them focus on a particular disciplinary area (e.g., ***5, 6, 8, 10, 21***). With this in mind, we think that this paper may provide a useful guide for researchers (both those new to the field of human-nature interactions and those with previous expertise) as well as policy makers, enabling them quickly to grasp a broad view of the field and develop more holistic thinking about the ecology and management of these interactions.

Conceptual framework

Our framework consists of four major components: (i) ***personalised ecology***, the set of direct sensory interactions that an individual person has with nature (***1, 2***) (see Fig. 1 for more details on its definition); (ii) its *drivers*, (iii) its *consequences*, and (iv) the *feedback loops* from the consequences to the drivers (Fig. 2). Adopting the COM-B model developed by Michie et al. (***22***), we considered personalised ecology to be driven by three major factors: *capability*, *opportunity* and *motivation* (Fig. 2). We also classified the consequences of personalised ecology into five broad categories, from both human and nature perspectives, as well as considering beneficial and adverse outcomes (note that *attitudes towards nature* could be seen as both *drivers* and *consequences* as these are closely linked to *motivation*; Fig. 2).

Literature review

We conducted a broad literature review with a structured search to identify concepts and theories that are useful to understand the four major components of the framework (Fig. 2). To achieve this, we developed a structured search query for the Web of Science database (1/3/2021) and explored literature from across diverse disciplines related to human-nature interactions, including ecology, conservation science, public health, immunology, urban planning, leisure, psychology and education. The search query included six phrases that are commonly used to refer to human-nature interactions in the above-mentioned fields ('human-nature interaction*' OR 'human-nature connection*' OR 'nature interaction*' OR 'nature connection*' OR 'nature experience' OR 'nature exposure*'). We limited consideration to those concepts and theories that were (i) developed to investigate specific topics focusing on human-nature interactions at the level of individual people, (ii) developed mainly to study topics focusing directly on interactions between people and nature, and (iii) more or less supported by empirical and/or anecdotal evidence. To avoid repetition, we did not include concepts and theories that were subsets of more general ones. Concepts and theories that are widely recognised but have not been formally named were included.

0ur structured literature review identified 39 relevant concepts and theories (Table 1). To make it easier to understand how the selected concepts and theories relate to each other, we placed them in our conceptual framework (Fig. 2). In the subsequent sections, we briefly discuss these concepts and theories and how each contributes to understanding the structure and dynamics of human-nature interactions. For convenience we start with the *drivers*, then move on to *personalised ecology* and *consequences*. For easier readability, we discuss the *feedback loops* in the *consequences* section.

Drivers

Opportunity

Opportunity is defined as all of the factors in a person's environment that make behaviour possible. It is divided into physical opportunity (e.g., the amount of wildlife and natural environments that a person can interact with) and social opportunity (e.g., family values and social norms, public safety) (***22***). In the field of environmental science, several concepts and theories attempt to explain the spatial and temporal dynamics of physical opportunity. For example, it is well-known that, at least in higher income societies, socio-economically advantaged groups of people tend to have more opportunities to obtain positive nature interactions (***3***). The positive relationship between wealth and the quantity and quality of neighbourhood nature is known as the **luxury effect**, which can occur either because wealthier individuals are better able to maintain greater amounts of vegetation in their neighbourhoods and/or because they can better afford to live in greener neighbourhoods (***3***). There is, however, a less well documented situation in which the quantity and quality of nature is greater in areas where poorer groups live (i.e., a **poverty effect**) (***23***). This can occur when being wealthier is associated with moving to less green environments (e.g., city centres). Luxury and poverty effects help explain why within populations the opportunity for positive nature interactions is typically spatially biased towards some groups of people (***2***).

Not only does opportunity vary spatially, it does so temporally. In much of the world, people's opportunities directly to interact with nature in their daily lives have been declining over the past several decades and may now be at low levels (***24***). This progressive loss of opportunity, referred to here as **nature scarcity**, is likely to be driven by several different but interrelated factors, such as loss of natural environments and their associated wildlife (especially common species), increase in the number and proportion of the global human population living in urban areas, and the overscheduling and micromanagement of children's lives (***5***).

In the field of conservation science, it has been suggested that, given the ongoing deterioration of ecosystems across the world, contemporary people are increasingly accustomed to a situation where the natural environment is impoverished (***25***). This gradual change in the accepted norms for the condition of the natural environment, the so-called **shifting baseline syndrome** (***25, 26***), is considered as one of the fundamental reasons behind nature scarcity because it can result in a progressive erosion of people's motivation to support pro-nature policies and management actions (***25***). Of course, shifting baseline syndrome can in some cases also occur in a positive direction, such as when the condition of the natural environment is improving through conservation or restoration strategies (e.g., urban greening, wildlife reintroduction, endangered species recovery).

Motivation

Motivation is all of the brain processes that energise and direct behaviour (it is often referred to as *orientation*; ***5***). It is divided into automatic motivation (e.g., emotional reactions) and reflective motivation (e.g., intentions) (***22***). It is widely accepted that an individual's emotional affinity to nature is one of the key motivational factors shaping people's personalised ecologies, and researchers in environmental psychology have developed diverse concepts and theories to measure it and understand its formation process. For example, **nature relatedness** is a psychological construct that describes how close is an individual's relationship with nature (***15***). This construct is multi-dimensional and often includes cognitive and affective strands, including empathy towards the natural world, as well as experiential and behavioural aspects. In the field of evolutionary psychology it has long been argued that people's emotional affinity towards nature is, at least partly, an innate trait, that is a genetically based evolutionary heritage, and this is the so-called **biophilia hypothesis** (***27***). This notion is based on the assumption that humans have evolved with the natural environment over millennia and thus are still innately attuned to nature. The biophilia hypothesis is closely related to the **savannah hypothesis**, which suggests that humans intrinsically prefer environments that contain key features of the savannah (e.g., grasslands with low vegetation, dispersed round-shaped trees) that were most likely to have aided their ancestors' survival (***28***).

People also often show strong avoidance responses to certain natural stimuli, settings or situations that are potentially harmful to them, so-called **biophobia** (***29, 30***). This takes various forms, such as apiphobia (fear of bees), arachnophobia (fear of spiders), ophidiophobia (fear of snakes), and entomophobia (fear of insects), and is thought to entail innate physiological responses to the perceived danger from non-human threats (***30***).

It is widely held that in urbanised regions, younger generations are losing emotional affinity to nature (e.g., ***31, 32***), referred to here as **nature apathy**, and this is largely due to a shift in preferences for electronic entertainment, such as television, computer games, and the internet (the **videophilia hypothesis**) (***31***). In addition, and perhaps more importantly, it has also been suggested that, not only does urbanisation decrease people's positive attitudes towards nature, but it can also increase negative ones (***30, 33***). The **urbanisation-disgust hypothesis**, developed within evolutionary psychology, suggests that shifts in the space where people encounter wildlife from outdoor natural settings to indoors due to urbanisation likely increases their biophobia because humans have evolved to avoid objects with a high risk of disease transmission (i.e., animals they encounter within their living spaces) (***30***).

Capability

Capability is an individual's capacity to engage in interactions with nature. It can be divided into physical capability (e.g., physical ability to climb mountains, the ear's ability to hear bird song) and psychological capability (e.g., skills to recognise species, orientation skills) (***22***). The discussion of human-nature interactions has to date largely focused on *opportunity* and *motivation* (***1, 2, 5, 21, 34***), and thus understanding of the role of *capability* in determining personalised ecologies remains relatively poor.

In the fields of environmental science and psychology, it has often been suggested that psychological capability plays an important role in shaping personalised ecologies. For example, it is well-known that people generally have limited ability accurately to perceive the biodiversity surrounding them, and thus there are significant differences between the direct interactions between people and nature that actually occur and those that the people concerned perceive to do so (***35***) (c.f., **people-biodiversity paradox**). Whilst such a tendency not to notice species, which we here term **nature blindness**, could be seen with regard to various taxa (e.g., insects, birds), it is considered to be more evident for plants compared to animals (so-called '**plant blindness**') (***36***). Plant blindness can be explained by a general lack of people's interest in and knowledge about plants, the visual homogeneity of these organisms, or the lack of visual cues such as movement (***36***).

Especially in higher income societies, there has been a recent gradual decline in the average level of both zoological and botanical natural-history knowledge among the general public, particularly children (***37***). Explanations for this loss of knowledge, referred to here as **nature ignorance**, include the decline in exposure to natural history through formal education systems, loss of overall interest in nature itself due to the rise in screen-based entertainment (see *Motivation* section), and the ongoing loss of biodiversity worldwide (see *Opportunity* section). Ironically, nature ignorance whilst foremost decreasing personalised ecologies may in some cases increase them. For example, it is suggested that the recent rise in some negative interactions of people with nature (e.g., attacks by large vertebrates) is, at least partly, a result of inappropriate and risk-enhancing human behaviours (e.g., walking an unleashed dog, closely approaching dangerous animals) (***19***).

Interrelated drivers

The three sets of drivers do not shape personalised ecologies independently, but rather are interrelated in many ways. For example, community values towards nature (*opportunity*) and levels of ecological knowledge (*capability*) are both likely to affect an individual's *motivation* to interact with nature, and

vice versa (***30, 34, 38***). Understanding the relationships among the drivers of personalised ecologies is a key challenge that has received relatively little attention.

Personalised ecology

There is growing interest in understanding how people's personalised ecologies vary spatially and temporally and determining how best to maximise the positive outcomes for both humans and nature (***1, 2***). In this context, there has been concern over the progressive, widespread decline in positive direct interactions of people with nature, the **extinction of experience** (***5, 39***). This is considered to be caused by two major sets of factors. The first is the loss of *opportunity* to interact with nature (i.e., nature scarcity). The second factor is the reduced inclination to engage with nature (i.e., nature apathy), which is likely associated with the rise in screen-based entertainment (i.e., videophilia). Although discussion of the extinction of experience has thus far largely centered on the importance of the loss of *opportunity* and *motivation* (***5***), it is also important to understand how the ongoing loss of *capability* (e.g., nature ignorance) contributes to the development of this phenomenon.

In contrast to the extinction of experience, there is an emerging growth trend in some kinds of negative direct interactions with nature (***7, 18, 19***). These include snake bites (***7***), shark bites (***18***) and attacks by large carnivores (***19***). This expansion of negative nature interactions (a component of the counterpoint to extinction of experience, the **expansion of experience**) is likely to be induced by environmental and social factors that increase the *opportunity* to experience negative nature interactions, such as increases in numbers of ecotourism opportunities, reductions in available natural undisturbed habitat due to urban and agricultural developments, increases in ecotourism to previously remote and undisturbed locations, growing familiarity of wild animals with people, and the decline in people's knowledge of how to behave appropriately when they encounter wildlife (i.e., nature ignorance) (***2***).

Consequences

Attitudes towards nature

Direct interactions with nature change people's attitudes towards nature (***5***) (Fig. 2). Indeed, it has been well demonstrated that nature interactions, especially during childhood, can play an important role in forging and strengthening an individual's positive emotions and attitudes towards nature (e.g., ***27, 40***), which we here term the **early nature experience hypothesis**. This idea is consistent with the biophilia hypothesis, which suggests that while biophilia is an innate human attribute, to be expressed it must be triggered through actual experiences of nature (***41***). Importantly, the early nature experience hypothesis

implies that the widespread loss of positive interactions with nature among young people can lead to large-scale erosion of people's favourable attitudes towards nature (***5***). This idea is widely shared amongst scientists, and thus the ongoing extinction of experience is increasingly viewed as one of the major threats to global environmental protection (***5, 20***).

Importantly, it is argued that increased positive attitudes towards nature through enhanced personalised ecologies can improve human wellbeing (e.g., ***42***), which we term here the **nature and happiness hypothesis**. Indeed, there is considerable evidence that an individual's levels of emotional affinity to nature are strongly associated with those of subjective health and wellbeing (e.g., ***42***), although the causal mechanisms involved are still under investigation. The nature and happiness hypothesis suggests that reinforcing the connection between people and nature could simultaneously contribute to increasing human happiness and pro-environmental attitudes.

Of course, *attitudes towards nature* could be seen as the driver of personalised ecologies, as these are closely linked to *motivation* towards engaging with nature. This implies that there exists a bidirectional relationship between *motivation* and *personalised ecology* (Fig. 2). Moreover, an individual's attitudes towards nature may influence other individuals' *motivation* to interact with nature, especially those in younger generations (***5***). For example, it is well-known that parental attitudes towards nature exert strong impacts on their children's attitudes (e.g., ***33, 38***), which we term the **nature inheritance hypothesis**. *Attitudes towards nature* can also often shape *opportunity* and *capability* (**Fig. 2**). For example, people who have greater pro-nature attitudes are more likely to reside in areas with greater opportunities (e.g., greener neighbourhoods) (***43***) and are more motivated to acquire knowledge about nature (***44***), which we term the **nature demand hypothesis**.

Benefits for humans

People obtain a wide array of health and wellbeing benefits from their personal interactions with nature (***6, 8–12***) (Fig. 2). These can be broken into three major categories: physical, psychological and social benefits (see below) (***6***). The health benefits of nature interactions could be viewed as **cultural ecosystem services** (or sometimes called '**psychological ecosystem services**'; ***9***), although relatively limited attention has been focused on them in the current ecosystem services framework (***9***). Below we briefly summarise the major concepts and theories associated with each of the three types of benefits from direct nature interactions. We will not describe in detail the mechanisms through which these benefits are produced as several recent reviews cover the topic (see ***6, 8–10***).

Physical benefits

In the field of public health, it has long been considered that nature interactions promote physical activity, which can have a wide range of physical health benefits, including enhanced physiological functioning such as muscular strength and the reduction of risk factors associated with chronic diseases (***6, 8, 10***). Indeed, natural/naturalised surroundings such as vegetated streetscapes and urban parks are generally associated with higher levels of physical activity in children and adults, including the elderly (***6***). However, the **green exercise hypothesis** proposes that physical activity in natural settings provides greater health and wellbeing benefits than equivalent exertion in indoor settings (***45***).

Along with benefits derived from physical activity, in the field of immunology it has been suggested that direct interactions with nature (albeit essentially non-sensory ones) improve human immune function, which can contribute to the prevention of non-communicable diseases, such as asthma, allergies, and cardiovascular diseases (***11, 12***). The well-established **hygiene hypothesis** suggests that contact with microbial communities in natural settings during particular developmental periods can improve immune function over the lifespan (***46***). This hypothesis has subsequently been refined and replaced by the **biodiversity hypothesis** and **old-friends hypothesis**, both of which suggest that exposure to diverse microbiomes (e.g., bacteria, fungi, protozoans) helps increase the ability of the immune system accurately to distinguish detrimental from beneficial bacteria, and that immune modulation of this kind can shape a wide variety of health outcomes (***11, 12***). As the role of environmental microbiomes in regulating the immune system has become more apparent, it is increasingly recognised that 'rewilding' environmental microbiomes in ecologically impoverished areas (e.g., cities) through ecological restoration can benefit public health (the **microbiome rewilding hypothesis**) (***47***).

Psychological benefits

In the field of environmental psychology, two complementary theories have been developed to explore the link between direct nature interactions and improved psychological health. First, the **stress recovery theory** is a psycho-evolutionary theory that views non-threatening natural scenes as restorative because they lead to a more positively-toned emotional state and decreased levels of physiological arousal (***48***). Second, the **attention restoration theory** suggests that excessive concentration can lead to 'directed attention fatigue,' and that interactions with nature engage a less taxing, indirect form of attention, thereby facilitating recovery of directed attention capacity (***49***). Importantly, there is some evidence that natural environments with higher biodiversity or greater abundance of species that people are likely to encounter provide greater psychological benefits to humans (***50***), which we here term the **biodiversity-wellbeing hypothesis** (c.f., people-biodiversity

paradox; ***35***). This hypothesis, as well as the microbiome rewilding hypothesis, has important implications for conservation, as it suggests that opportunities exist jointly to conserve biodiversity and improve human health.

Social benefits

In the field of public health, it has been suggested that nature interactions promote social interaction within neighbourhoods, which may in turn contribute to improved social health (***6***), which we term here the **nature and social cohesion hypothesis**. Indeed, natural environments often provide people with opportunities to interact with other members of local communities, and this is likely to increase community ties and minimise social isolation (***6***).

As the various health-related benefits derived from nature interactions become more apparent, it is increasingly accepted among policy makers and practitioners that a regular 'dose' of nature is a necessary ingredient for maintaining a healthy life (***9***). Indeed, there have been extensive efforts to develop strategies and programmes aimed at promoting people's *opportunity* and *motivation* directly to interact with nature (i.e., **nature-based health interventions**) (***17***). This suggests that positive feedback loops exist in which the consequences of personalised ecologies accelerate further interactions with nature (Fig. 2). Of course, improvements of physical and psychological health conditions as a result of nature interactions are also likely to increase people's personalised ecologies, as they contribute to increased *capability* to participate in these interactions.

Costs for humans

It has often been suggested that rising incidences of several major health and developmental problems in children are, at least partly, due to ongoing loss of positive interactions with nature (i.e., the extinction of experience) (***51***). These negative health consequences due to disconnection from nature have been called a **nature-deficit disorder** (***52***). Although not a formal diagnosis, this notion is supported by abundant evidence demonstrating that lower levels of exposure to nature during childhood are associated with increased risk of poor health outcomes, such as depression, behavioural problems, and attention deficit/hyperactivity disorder (***53***).

As discussed earlier, direct interactions with nature have not only positive consequences for humans but also negative ones (Fig. 2), often referred to as components of **human-wildlife conflict** (***54***) or **ecosystem disservices** (***55***). These negative nature interactions vary in intensity from typically

minor (e.g., perceiving noise nuisance) to severe (e.g., being attacked by large carnivores) and vary in frequency from rare to common (***2***). Importantly, at least in some lower income countries, socio-economically disadvantaged people may experience these negative nature interactions more frequently, because they tend to live in regions where there are more potentially harmful wildlife species (e.g., venomous snakes) and undertake activities that place them at higher risk (e.g., agricultural activities) (***2***). In other words, poor people have more *opportunity* to experience negative interactions with nature, which could be viewed as a part of the poverty effect (see *Opportunity* section). Reducing wealth-related inequalities in the frequency and intensity of negative interactions with nature is recognised as a key challenge for public health.

While a great deal of effort has been made to develop concepts and theories regarding the benefits of interacting with nature, far less has been concentrated on those concerning the costs for humans (Fig. 2). This dearth of research effort on the negative aspects of personalised ecologies is potentially problematic, given the recent rise in some negative interactions of people with nature, and their associated social costs, worldwide (i.e., the expansion of experience) (***7, 18, 19***). In addition, in urbanised societies there has been growing concern over 'novel' negative interactions with wildlife that lie beyond those that have traditionally been addressed in the context of human-wildlife conflict (e.g., being stung by invasive wasps, hearing sounds of animals that cause anxiety) (***55***). Further theoretical work in this area will be crucial to advancing understanding of what kinds of negative consequences direct interactions with nature have for humans, how they are derived, and how they can be minimised.

Benefits for nature

Direct human interactions with nature can confer benefits for nature, both directly and indirectly (***2***) (Fig. 2). For instance, some types of nature interactions, such as wildlife gardening and feeding squirrels by hand, can be viewed as a benefit in terms of resource gain by wild organisms (***21***); benefits to parts of nature may not, of course, necessarily translate into benefits to nature at large (e.g., growing the food fed to squirrels, and any increases in squirrel numbers, may have larger negative effects). Importantly, such gains are often particularly large in areas in which affluent people live and use, and this is one of the core drivers of the luxury effect (see *Opportunity* section). Likewise, natural environments with higher human presence (e.g., urban parks, popular ecotourism sites) can reduce predation risk for some prey species because predators avoid these environments (**human shield effect**) (***56***). Human shield effects could be seen as benefits to prey species, as they can offer a relatively safe area, which enables them to be less watchful and to allocate time to other fitness-enhancing activities (e.g., foraging, finding a mate, parental care) (***56***). These effects often make individuals of prey species bolder towards humans, as well as predators, due to lower overall

fearfulness towards potential threats (***56***). Such behavioural changes will increase people's *opportunity* to encounter animals, resulting in more frequent and intense interactions with them, which we name **human-wildlife feedback** (Fig. 2).

On a longer-term scale, there is a widely held assumption that improving people's personalised ecologies can increase their support for conservation policies and actions, which may in turn have a wide range of positive consequences for nature such as the recovery of endangered species and restoration of wildlife habitats (***5, 57***). This assumption, which we call the **nature benefit hypothesis**, stems from the idea that direct interactions with nature can contribute to development of pro-environmental attitudes and behaviour both directly (i.e., the early nature experience hypothesis) and indirectly through reducing levels of the shifting baseline syndrome (***5, 25***). It is also in accordance with the idea that exposure to nature reduces impulsive and selfish decision-making in humans, which may promote environmentally sustainable behaviour and decision-making (***58, 59***), which we term here the **nature and sustainability hypothesis**. The nature benefit hypothesis has important implications for conservation because it suggests that a well-designed policy and strategy for improving people's personalised ecologies, particularly in urban areas, can yield beneficial results for both humans and nature. Of course, the resultant improvement of the natural environment through enhanced personalised ecologies will further facilitate people's nature interactions as it directly increases their *opportunity* to engage with nature (Fig. 2).

Costs for nature

Many types of human interactions obviously have negative consequences for nature (Fig. 2). These impacts range from the potentially minor, such as increased levels of stress induced by human recreational use of greenspace, to the severe, such as greater mortality risk due to roadkill. Not surprisingly, situations often arise in which humans obtain benefits from interactions with nature but bring costs to nature (e.g., overuse of protected areas for recreational purposes). In such cases, increases in direct interactions with nature may lead to subsequent decreases in personalised ecologies because such costs often result in a reduction in people's *opportunity* to interact with nature (e.g., decline in wildlife populations), negative human-wildlife feedback (Fig. 2). This raises a significant challenge for policy-makers in wildlife conservation as to how best to maximise the positive outcomes for humans while minimising the negative impacts for nature. It is important to note that these negative impacts can be reduced to some extent by mitigating nature ignorance rather than just by reducing people's interactions with nature (e.g., the number of greenspace users) themselves. Indeed, if people obtain knowledge about how to behave in nature, they may use it in a way that does less harm to it (e.g., maintaining appropriate distances from wildlife).

Of course, some types of human interactions with nature can cause costs for both humans and nature, human-wildlife conflict (***60***). Such a phenomenon, to a greater or lesser extent, occurs across all countries and regions, and takes a wide variety of forms, including accidentally hitting a deer while driving a car and being killed by an elephant disturbed in a protected area which is subsequently relocated or culled. Human-wildlife conflict is increasing in both frequency and severity worldwide and is expected to continue to escalate due to the ongoing growth of human populations and the associated increase in demand for natural resources (i.e., the expansion of experience; ***60***).

Challenges ahead

Despite remarkable progress in understanding direct human-nature interactions, several challenges lie ahead. First, there is a paucity of theoretical principles with regard to some domains within the field. Indeed, we found that while considerable effort has been made to develop concepts and theories regarding the *Motivations* and *Benefits for humans* domains, far less effort has been concentrated on others (especially the *Capability*, *Costs for humans* and *Costs for nature*) (Fig. 2). Given the crucial role that the latter components, as well as the former, play in shaping the dynamics of direct human-nature interactions, this unbalanced research effort is clearly a major barrier to the growth of this field.

The second, and perhaps most important, challenge is how best to advance further integration of knowledge from the different disciplines addressing human-nature interactions. Many studies, particularly those arising from social sciences and public health, are 'human-oriented', foremost concerned with the implications of personalised ecologies for people, and often addressing the nature component in quite generic terms. Many others, particularly arising from the environmental sciences, are 'nature-oriented', focused on the implications for the abundance and distribution of wildlife, and often treating the human causes and consequences of personalised ecologies quite superficially. Obviously, the two approaches are complementary, and much will be gained by improving the dialogue between them. For example, there are many sophisticated tools available within ecology for evaluating biological characteristics of the ecosystem or landscape, such as species richness and vegetation structure, and they could provide valuable insight when using the human-oriented approach. Similarly, social sciences have developed a substantial body of theory related to human beliefs, attitudes and behaviour, and researchers adopting the nature-oriented approach can gain many useful insights from them.

Caveats

Our analysis inevitably has inherent limitations. First, there are doubtless highly relevant studies of direct human-nature interactions in the English-language literature that we did not find, although we used a broad search strategy and cover a broad range of disciplines. Second, it is quite possible that some valuable studies were not taken into account because they have been published in languages other than English. Given that the form and implications of human-nature interactions can vary substantially across societies with different cultural backgrounds, exploring such non-English language publications might add valuable insight to the field. Third, for the purpose of the present study we only considered the concepts and theories that focused on human-nature interactions at the level of individual people. However, it would be also beneficial to consider those focusing on interactions at the level of society (i.e., society's collective interactions with nature). Indeed, these two levels of interactions with nature are likely to be influenced by each other, and thus considering the key social, cultural and historical factors shaping the latter type of interactions with nature may help understand the former.

Implications

Our proposed framework may provide several contributions to the field, as it (i) provides a common platform for better communication among researchers with different disciplinary perspectives; (ii) offers greater theoretical clarity, which will aid in synthesis of past work and hypothesis generation for future work; and (iii) covers a wide breadth of inter-related issues concerning human-nature interactions, thereby encouraging holistic thinking about these interactions. More importantly, our framework also has several important practical implications: it (i) provides policy-makers with theoretical grounds for their decision-making, which may in turn help guide evidence-based policy formulation; and (ii) shows that the various issues and challenges related to these interactions, that have traditionally been handled by different policy fields, are closely related to each other, thereby potentially facilitating the development of cross-sectoral policies that can lead to improved outcomes across multiple domains.

Conclusion

Our paper suggests that theoretical and empirical advances in understanding of direct human-nature interactions have generated the potential to transform this field into a robust, more holistic science. Given the current emphasis on, and trend towards, cross-disciplinary initiatives within much of the scientific community, it is timely to advance that science. More importantly, such a unified science would contribute greatly to enhancing the sustainability of human-nature relationships. Indeed, our

conceptual framework clearly shows that a well-planned policy for improving people's personalised ecologies can yield beneficial consequences for both humans and nature. In other words, a proper management of personalised ecologies will be key to ensuring the healthy and sustainable future of people and the planet. It is now time to begin a new era of the interdisciplinary science of human-nature interactions, and its future holds enormous promise.

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Acknowledgements

We are grateful to D.T.C. Cox, M.J. Evans, T. Kubo, C. McKinnon, M.J. Miller and three anonymous reviewers for comments on the manuscript. We thank R. Hoshino for creating the illustrations used in Figure 2. M.S. was supported by the Japan Society for the Promotion of Science (grant no. 20H04375), the Toyota Foundation (grant no. D19-R-0102), the Research Institute for Humanity and Nature (RIHN: a constituent member of NIHU): Feasibility Project (Project No. 14200158), and the UTokyo Global Activity Support Program for Young Researchers.

Author contributions

Both authors conceived the work, drafted the manuscript, edited and approved the final version.

Competing interests

The authors declare that they have no competing interests.

Figure legends

Figure 1. The definition of personalised ecology. In this paper we define personalised ecology as the set of direct sensory interactions that an individual person has with nature (see Table 1). These interactions are generated through multiple sensory channels such as sight, hearing, touch and smell (***2***). Our definition of personalised ecology thus includes a wide diversity of human interactions with nature, such as (**a**) walking a dog in an urban greenspace; (**b**) viewing trees through a window; (**c**) feeding a bird by hand; (**d**) watching a whale; (**e**) being bitten by a mosquito; and (**f**) hitting a deer whilst driving a vehicle. Following previous studies (***1, 2***), we exclude 'interactions' with organisms that are not self-sustaining (e.g., playing with domestic pets, viewing crops on agricultural land) and those through the media (e.g., viewing nature documentaries, viewing nature scenes through virtual reality). Photos are from Pixabay (https://pixabay.com/ja) (**a, b, c, e**) and iStock (https://www.istockphoto.com/jp) (**d**, **f**).

Figure 2. A unified conceptual framework for understanding the dynamics of direct human-nature interactions. This consists of four major components: (i) *personalised ecology* (the green-coloured domain), (ii) its *drivers* (*capability*, *opportunity* and *motivation*) (the blue-coloured domain), (iii) its *consequences* (benefits and costs for both humans and nature) (the red-coloured domain), and (iv) the *feedback loops* from the consequences to the drivers (the grey-coloured domain). *Attitudes towards nature*, which is one of the five major consequences of personalised ecologies, is closely linked to *motivation*, so these two variables were integrated into the single 'Motivation' box (the purple domain) (note: this box belongs to both the *Drivers* and *Consequences* domains). Since *motivation* and *personalised ecology* are influenced by each other, a bidirectional arrow connects them (see *Attitudes towards nature* section). The numbers shown in each component indicate the ID of each concept/theory in Table 1 (the concepts and theories were placed in the domains that are most related to them).

Table 1. Concepts and theories concerning human-nature interactions. Each one is defined, the discipline with which it is closely related is listed, and one or more key references provided. For each of the concepts and theories we also provide the major component of our conceptual framework with which it is most closely related (see **Fig. 2**).

No.	Theory/concept	Definition	Related discipline	Key reference	Related component
1	Personalised ecology	The set of direct sensory interactions that an individual person has with nature	Ecology	***1***	Personalised ecology
2	Luxury effect	Higher number of species and their abundance in the areas where wealthier groups of people live and which they use	Ecology	***3***	Drivers (opportunity)
3	Poverty effect	Higher number of species and their abundance in the areas where poorer groups of people live and which they use	Ecology	***23***	Drivers (opportunity)
4	Nature scarcity	Progressive decline in people's opportunities to experience interactions with nature	Conservation science	***24***	Drivers (opportunity)
5	Shifting baselines	Long-term changes to an environment go unrecognised because what is perceived as natural shifts with succeeding generations of scientists and other observers	Conservation science	***25, 26***	Drivers (opportunity)
6	Nature relatedness	Subjective sense of connection people have with the natural world	Psychology	***15***	Drivers (motivation)
7	Biophilia hypothesis	People are innately attracted to animals and other living things	Evolutionary psychology	***27***	Drivers (motivation)
8	Savannah hypothesis	Humans prefer open, savannah-like landscapes as they would have favoured survival by our early ancestors	Evolutionary psychology	***28***	Drivers (motivation)
9	Biophobia	A partly genetic predisposition to retain feelings of strong negative responses to certain natural stimuli, which have been threats during human evolution	Evolutionary psychology	***29***	Drivers (motivation)
10	Nature apathy	Progressive decline in people's interest in nature	Education; Psychology	***32***	Drivers (motivation)

11	Videophilia hypothesis	Younger generations are losing inclination towards nature largely due to a shift in preferences for electronic entertainment	Leisure	***31***	Drivers (motivation)
12	Urbanisation-disgust hypothesis	Living in urban areas increases the intensity of feelings of disgust towards animals	Evolutionary psychology	***30***	Drivers (motivation)
13	People-biodiversity paradox	Although people tend to prefer biodiverse environments, and obtain greater wellbeing benefits from these, they generally have limited ability accurately to perceive the biodiversity surrounding them	Conservation science	***35***	Drivers (capability)
14	Nature blindness	Tendency of people not to see or notice certain groups of animals and plants in their environment	Conservation science	***36***	Drivers (capability)
15	Nature ignorance	Progressive decline in the average level of natural-history knowledge among the general public	Education	***37***	Drivers (capability)
16	Extinction of experience	Progressive loss of daily interactions between people and nature	Conservation science	***5, 39***	Personalised ecology
17	Expansion of experience	Progressive increase in some kinds of interactions of people with nature	Ecology; Public health	***18, 19***	Personalised ecology
18	Early nature experience hypothesis	Direct nature experiences during childhood promote pro-environmental attitudes and behaviour	Conservation science; Psychology	***40***	Consequences (attitudes towards nature)
19	Nature and happiness hypothesis	Increased emotional connection to nature promotes psychological health	Psychology	***42***	Consequences (attitudes towards nature)
20	Nature inheritance hypothesis	Resemblance in beliefs and attitudes towards nature between parents and their children	Psychology	***33, 38***	Feedback loops
21	Nature demand hypothesis	People who have greater positive attitudes towards nature are more likely to seek opportunities, and develop capabilities, that allow them to interact with nature	Psychology	***44***	Feedback loops
22	Cultural ecosystem services	Nonmaterial benefits people obtain from ecosystems through spiritual enrichment, cognitive development, reflection, recreation, and aesthetic experiences	Conservation science	***9***	Consequences (benefits for humans)
23	Green exercise hypothesis	Physical activity in natural settings provides greater health and wellbeing benefits than equivalent exertion in indoor settings	Public health	***45***	Consequences (benefits for humans)

24	Hygiene hypothesis	Early childhood exposure to particular microorganisms protects against allergic diseases by contributing to the development of the immune system	Immunology	***46***	Consequences (benefits for humans)
25	Old-friends hypothesis	Humans co-evolved with pathogens and other microorganisms to the point that exposure to these symbionts is used in the development and regulation of immune systems	Immunology	***12***	Consequences (benefits for humans)
26	Biodiversity hypothesis	Contact with natural environments and biodiversity (especially microbes) enriches the human microbiome, promotes immune balance and protects from allergy and inflammatory disorders	Immunology	***11***	Consequences (benefits for humans)
27	Microbiome rewilding hypothesis	Restoring biodiverse habitats can rewild the environmental microbiome to a state that enhances primary prevention of human disease	Immunology	***47***	Consequences (benefits for humans)
28	Stress reduction theory	Nature has a stress-reducing and restorative influence on people	Psychology	***48***	Consequences (benefits for humans)
29	Attention restoration theory	People can concentrate better after experiencing nature	Psychology	***49***	Consequences (benefits for humans)
30	Biodiversity-wellbeing hypothesis	Natural environments with higher biodiversity provide greater psychological benefits to humans	Conservation science	***50***	Consequences (benefits for humans)
31	Nature and social cohesion hypothesis	Nature interactions promote social interaction within neighbourhoods, which in turn contributes to increased social cohesion	Public health	***6***	Consequences (benefits for humans)
32	Nature-based health intervention	Any programme, activity or strategy that aims to engage people in nature-based experiences with the specific goal of achieving improved health and wellbeing	Public health	***17***	Feedback loops
33	Nature-deficit disorder	People, especially children, are spending less time outdoors, resulting in a wide range of health and developmental problems	Public health	***52***	Consequences (costs for humans)

34	Human-wildlife conflict	Any interaction between humans and wildlife with negative consequences for both parties	Conservation science	***54***	Consequences (costs for humans; costs for nature)
35	Ecosystem disservices	Ecosystem-generated functions, processes and attributes that result in negative consequences for people	Conservation science	***55***	Consequences (costs for humans)
36	Human shield effect	Prey species use humans as a shield from natural predation	Ecology	***56***	Consequences (benefits for nature)
37	Human-wildlife feedback	Direct human interactions with nature alter the behaviour, abundance and distribution of wildlife, which can in turn either increase or decrease the frequency and intensity of these interactions	Ecology	***21***	Feedback loops
38	Nature benefit hypothesis	Nature benefits, through increased support for conservation policies and action, when people increase their level of direct interactions with nature	Conservation science	***57***	Consequences (benefits for nature)
39	Nature and sustainability hypothesis	Exposure to nature reduces impulsive and selfish decision-making in humans, which may promote environmentally sustainable behaviour and decision-making	Psychology	***58, 59***	Consequences (benefits for nature)

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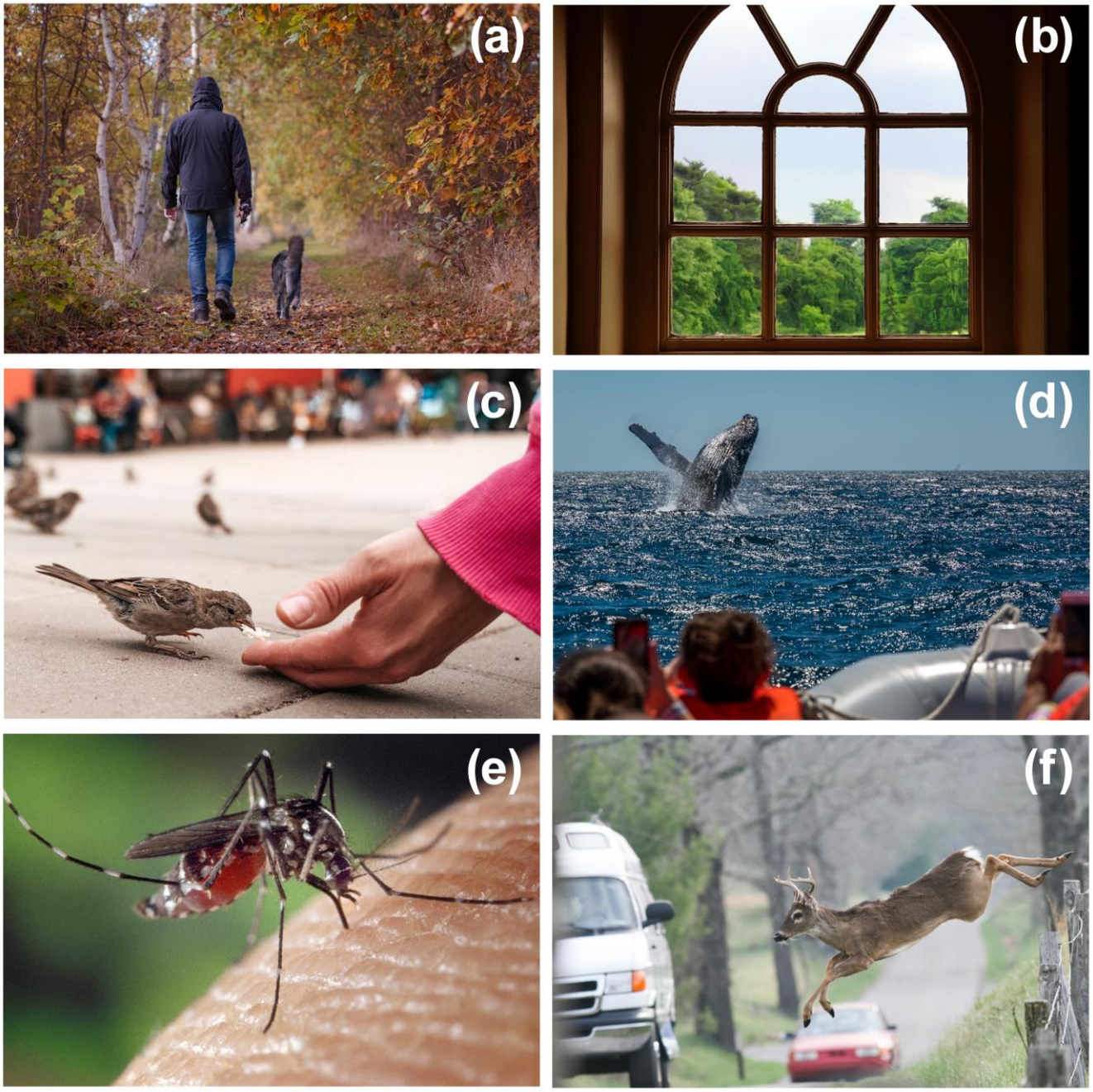

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