

The Health Benefits of Urban Nature: How Much Do We Need?

DANIELLE F. SHANAHAN, RICHARD A. FULLER, ROBERT BUSH, BRENDA B. LIN, AND KEVIN J. GASTON

Over 30 years of research has shown that urban nature is a promising tool for enhancing the physical, psychological, and social well-being of the world's growing urban population. However, little is known about the type and amount of nature people require in order to receive different health benefits, preventing the development of recommendations for minimum levels of exposure and targeted city planning guidelines for public health outcomes. Dose–response modelling, when a dose of nature is modeled against a health response, could provide a key method for addressing this knowledge gap. In this overview, we explore how “nature dose” and health response have been conceptualized and examine the evidence for different shapes of dose–response curves. We highlight the crucial need to move beyond simplistic measures of nature dose to understand how urban nature can be manipulated to enhance human health.

Keywords: dose–response, well-being benefits, green space, ecosystem services, ecosystem benefits.

Within 30 years, 70% of the world's human population will live in cities (World Health Organization 2013). The shift to an increasingly urbanized population will have major implications for health, because more people will be exposed to the chronic and noncommunicable conditions that are disproportionately common in cities; these include conditions such as cardiovascular disease, high blood pressure, and obesity (Dye 2008). Urban nature has the potential to provide an inexpensive intervention to assist in addressing many of these health issues, because there are now demonstrable links between exposure to nature and physical, psychological, and social well-being (Keniger et al. 2013, Hough 2014).

A growing body of evidence has begun to reveal how specific elements of nature enhance health and well-being (Jackson et al. 2013, Keniger et al. 2013). Nature functions in ways that alter the physical environment that people live in, thereby reducing health risks; these are called *biophysical ecosystem services*. For example, vegetation can filter pollutants from the air and buffer the urban heat island effect, potentially reducing the prevalence of respiratory infections or heat-related illnesses (Bolund and Hunhammar 1999, Lovasi et al. 2008, O'Neill et al. 2009, Jackson et al. 2013). In addition to such direct effects, nature can also indirectly influence health by mitigating the risks associated with other areas of people's lives or by encouraging positive health behaviors. For example, people may be more likely to exercise where the natural surroundings provide an interesting, pleasant, and safe environment (Timperio et al. 2008,

Lee et al. 2013), potentially leading to reduced obesity, diabetes, mental illness, and other health issues associated with sedentary lifestyles (Haskell et al. 2007). Exposure to nature can also have restorative effects, potentially reducing the effects of stress in a person's life (Hartig et al. 1991, Beil and Hanes 2013, de Vries et al. 2013, Ratcliffe et al. 2013). Many of these kinds of indirect benefits of nature can be heavily reliant on an individual's perceptions of and experiences within natural environments, as well as personal preferences (Hartig et al. 2014). All of these benefits of urban green space occur alongside a range of other positive outcomes, including enhanced biodiversity conservation and environmental sustainability (Tratalos et al. 2007, Tzoulas et al. 2007).

One important effect of urbanization is that people are exposed to reduced levels of nature in these highly altered environments (Turner et al. 2004). Consequently, the full array of health benefits that nature can provide are unlikely to be realized without specific interventions that aim to (a) enhance nature in cities and (b) connect people with the nature around them. These interventions are likely to be particularly useful for achieving public health outcomes if they prove cost effective, particularly when considering the full range of services and benefits that can be provided by urban nature (Hartig et al. 2014). Both interventions require an understanding of the types and amount of nature required for the intended physical, social, or psychological health outcomes. However, despite the fact that there is a growing body of scientific evidence on the nature–health connection spanning over 30 years, almost all the evidence so far is

correlative (Frumkin 2003, Keniger et al. 2013). Therefore, much remains to be learned about how much or what type of nature is required for the range of possible health benefits.

Dose–response modeling is commonly used in the health sciences and provides an appealing quantitative approach for informing guidelines on nature-based health interventions. In general terms, this approach involves modeling the effect of a dose of a substance or activity on a causally linked health response of an individual or a population (Altshuler 1981). The appeal of the approach stems from the fact that it could assist in developing minimum-dose recommendations of exposure to nature for individuals similar to other public health recommendations for physical activity (Powell et al. 2011) or fruit and vegetable consumption (US Department of Agriculture and US Department of Health and Human Services 2010). Such recommendations are simple but with potentially substantial public health outcomes across a population, and they can be easily communicated (Whitelaw 2012, Hartig et al. 2014). Dose–response modeling is not without difficulties; in particular, it offers significant analytical challenges because health responses of individuals and populations can be influenced by a great range of factors, including gender, experience, preferences, culture, or age (Whitelaw 2012, Hartig et al. 2014). However, even with these challenges, the dose–response approach is generally considered a useful tool for simplifying complexity and for providing guidance for self-regulating behaviors that enhance health outcomes (Whitelaw 2012, Hartig et al. 2014).

Importantly, population-level studies on the dose–response relationship between health and nature could also assist in developing rules of thumb for planning green space in urban environments; ultimately, these could be used to deliver the best health outcomes for the majority of the population. These guidelines will take different forms when considering health outcomes that simply rely on biophysical ecosystem services versus those that require active engagement or use of natural spaces. Although simple physical planning guidelines will be appropriate for the former, the latter is likely to require additional social strategies (Zhou et al. 2011, Lin et al. 2014). This information will be particularly valuable for cost-effective spatial planning in cities, where ecological restoration is expensive and subject to strict spatial constraints and quantifiable information on the multiple benefits that arise from urban green space will help guide efficient investment.

Despite the potential utility of the dose–response approach, the concept has rarely been explicitly employed in the context of the nature–health connection. In the first and perhaps the only study in which this has been done to date the impacts of “green exercise,” or exercise in green environments, were examined on self-esteem and mood (Barton and Pretty 2010). The study used a meta-analytical approach to show that the greatest effect of green exercise occurs within very short (5-minute) time periods. We argue that this dose–response concept has a much wider application than has so

far been realized. Here, we explore the utility of the dose–response concept for the nature–health connection with the aim of providing an overview of how it can be conceptualized at both the population and individual level. We first explore the theory behind the concepts of *dose* and *response*, and use a qualitative review approach to examine how existing literature on the nature–health connection fits within this paradigm. Second, we identify the possible shapes of the curves for different health responses, and review a range of factors that could affect these relationships. Finally, we propose potential ways forward amid this complexity.

Measuring nature dose

In the health sciences, “dose” is measured in a range of ways, reflecting the diverse pathways through which substances or activities can influence health or enter the body. For example, at the individual level, dose can be measured as the amount of a substance in a person’s blood or lungs or the frequency at which a drug is administered. Nature dose was first explicitly labeled by Barton and Pretty (2010), who simply measured the time people spent exercising in green environments. In retrospect, the concept has also clearly been employed in a range of additional studies, but it has been defined in different ways by health scientists and ecologists.

The majority of research on the nature–health link has been led by health scientists and commonly uses coarse variations in nature to measure dose, such as the contrasting scenes of *natural* and *built* or *urban* and *rural* (figures 1c and 1d show examples of this approach; Hartig et al. 2003, Lachowycz and Jones 2012, Beil and Hanes 2013). Proxy measures for nature are also often employed, such as the proportion of a landscape covered by public parkland or green space (figure 1b provides an example; Maas et al. 2006, Mitchell and Popham 2008). These studies have shown unequivocally that human well-being responds to the presence of nature and that the scale of response can vary with duration of exposure. However, a simplistic approach to defining nature limits any clear understanding of how its variation influences the scale of the health response. In contrast, studies led by ecologists measure nature dose using ecological features such as vegetation cover, plant and bird species richness, and number of habitats (figure 1a provides an example; Fuller et al. 2007, Dallimer et al. 2012, Hanski et al. 2012), but they rarely consider other important human factors, such as the time a person spends with nature. However, these studies are important because they have shown that variation in the types of nature, not just its presence, can be important for delivering a range of well-being outcomes.

There are a range of challenges associated with defining nature dose, largely because it can be framed in a social context as well as an objective reality (Hartig et al. 2014). However, providing that a mechanistic approach is taken, the construct of “exposure” can provide a useful way to create more meaningful measures of nature dose and draw together expertise from the health, social, and ecological sciences. Measures of exposure are used when direct measures

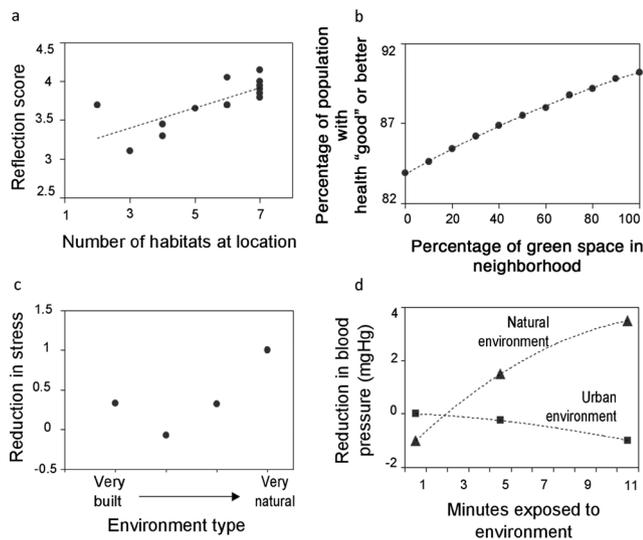


Figure 1. Examples of the dose–response relationship between nature and measures of health or well-being from previous studies; (a) psychological well-being (“reflection”) in response to exposure to different numbers of habitat types in Sheffield, United Kingdom (Fuller et al. 2007); (b) the relationship between green space cover (in a 3-kilometer radius around the home) and the percentage of respondents stating their health is “good” or better (adapted from Maas et al. 2006 to show the inverse of the data originally presented); (c) the change in stress levels in response to different landscape types (adapted from Beil and Hanes 2013 to show the inverse of the stress measure originally presented); (d) the change in mean arterial diastolic blood pressure over time during exposure to urban and natural settings in California (adapted from Hartig et al. 2003 to show only the first section of the experiment where participants were not exercising).

of a substance in a person’s body are difficult or expensive to collect or the pathway to a health response is indirect (Kriebel et al. 2007). For example, exposure has been used to generate minimum daily recommendations for physical activity; in this case, time, effort, and frequency of activity are considered important aspects of dose (Haskell et al. 2007). Thus, there are three key components of exposure: the *intensity of exposure* (how much), the *frequency of exposure* (how often), and the *duration of exposure* (how long; Kriebel et al. 2007, Smith 1992). Here, we describe how these can be adapted to measure nature dose.

Intensity of nature exposure. The quality and quantity of nature elements can both provide useful measures of intensity. For studies that focus on health and well-being outcomes at the population level, quantity of nature has been measured in a range of ways, from counting the number of street trees in a neighborhood (e.g., a negative correlation was found between the number of street trees and asthma prevalence in children; Lovasi et al. 2008) to the use of remotely sensed

data, such as percentage of vegetation cover in a landscape (e.g., a negative correlation was found between rates of assault and burglary and tree cover; Wolfe and Mennis 2012). Other studies have used proxies to measure quantity of nature: for example, the area of land designated as green space within a neighborhood has been found to correlate with both all-cause mortality and mortality from cardiovascular disease (Mitchell and Popham 2008). The quality of nature has also been measured in a range of ways; the most notable attempts assessed ecologically relevant measures of quality, such as bird species richness and number of habitats, both of which have shown positive correlations with individual-level psychological well-being (Fuller et al. 2007, Dallimer et al. 2012). Other aspects of nature quality that could conceivably have links with human health and well-being include vegetation structure (with a possible connection to mental health and well-being through the provision of a visually complex but undemanding environment; Ulrich 1983, Kaplan and Kaplan 1989, Berman et al. 2008). However, preferences and perceptions will influence the extent to which these measures of nature are relevant or important for different people (Hartig et al. 2014). Conceivably, other measures of nature quantity, such as leaf area indices, could also be employed in a dose–response context, because this property has direct links with biophysical ecosystem services, such as the heat regulation capacity of vegetation (Hardin and Jensen 2007).

Frequency of exposure. Frequency can be measured as the number of times a person is exposed to a nature element during a particular time frame, and in some instances, the pattern of exposure (e.g., cyclic, random, or intermittent) may also be important. The way an individual’s health responds to different frequencies of exposure to nature has received very little attention to date, though it is likely to be important in many contexts and across different time frames. For example, frequent views of nature during a short-term period (e.g., during the day) could cumulatively provide relief from mental fatigue (Kaplan 2001). In contrast, exercise conducted in green environments may need to occur on a repeated basis over a much longer time frame for a person to receive enhanced cardiovascular benefits (Bird 2004, Pretty et al. 2005).

Duration of exposure. Duration can simply be considered as the time during which a person is exposed to a nature element. There has been some investigation into the effects of duration of exposure at the individual level for some well-being responses, and these studies show that the rate of improvement can change over even very short time periods (psychological well-being, Barton and Pretty 2010; blood pressure as shown in figure 1d, Hartig et al. 2003). Duration of exposure should be measured at time scales that are relevant for the health response of interest. For example, when measuring the effects of vegetation cover on cardiovascular disease, the number of years a person lived in a particular landscape may be most relevant. However, when examining

the short-term cognitive benefits of viewing nature, the duration of interest may be the very short term, perhaps only minutes.

Intensity, frequency, and duration of exposure could all be more or less important than each other for any particular health response, and careful consideration of the mechanistic pathways involved will be necessary to determine the most appropriate measures for a particular study. For example, the duration of exposure to nature may be more important than the quality or quantity of nature itself for improved psychological well-being measured at the individual level, or having an orientation toward nature could be important for determining whether a person responds positively to nature at all (Shanahan et al. 2015). In contrast, when considering biophysical ecosystem services such as temperature regulation, the quantity or type of vegetation across a city may be the most important factor that influences the prevalence of heat-related illness in the population (Hardin and Jensen 2007, O'Neill et al. 2009).

Health responses to nature

Research has now demonstrated links between doses of nature and a remarkable number of health and well-being responses (Keniger et al. 2013). Population-level studies have shown that increased green space is associated with reduced all-cause mortality and mortality from cardiovascular disease (Mitchell and Popham 2008, Donovan et al. 2013), reduced asthma prevalence (Lovasi et al. 2008), and enhanced general or self-reported health (Maas et al. 2006, Groenewegen et al. 2012). Other studies have found no association between green space cover and mortality, or even higher mortality in greener cities, suggesting that health benefits might be best measured at finer scales or that the effects vary between locations (Richardson et al. 2010, 2012). A key pathway to health outcomes such as reduced cardiovascular disease may simply be increased exercise where green space provision is higher (Humpel et al. 2002, Kaczynski and Henderson 2007). However, research into green exercise is beginning to reveal that nature is likely to provide health benefits beyond those expected through exercise alone (Mitchell 2013, Richardson et al. 2013).

Individual-level studies have revealed relatively strong associations between exposure to nature and improved healing times (Ulrich 1984), reduced allergies (Hanski et al. 2012), and enhanced social cohesion (Groenewegen et al. 2012). In the immediate short term, exposure to nature has also been shown to correlate with reduced stress (Van den Berg and Custers 2011), improved cognitive ability (Berman et al. 2008, Han 2009), and enhanced happiness (MacKerron and Mourato 2013). The most significant body of research to date has shown a strong positive correlation between exposure to nature and psychological well-being measured in a range of ways, including mental restoration, self-esteem, attachment, and anger (Hartig et al. 2003, Fuller et al. 2007, Barton and Pretty 2010, Dallimer et al. 2012); cognitive function (commonly assessed using measures of attention;

Tennessen and Cimprich 1995); systolic and diastolic blood pressure and heart rate (Hartig et al. 2003, Lee et al. 2011); and recovery times (Ulrich 1984; see figure 1 for examples).

As indicated above, well-being responses can be measured at both the individual and population scales and at different time scales, depending on the outcome of interest. At the population scale, the proportion of people that responds to different doses of nature is generally of interest (i.e., the prevalence); this is the approach used by Mitchell and Popham (2008), who found lower rates of mortality from cardiovascular disease and all-cause mortality in neighborhoods with higher levels of green space. At an individual level, a health or well-being response could include a change in state: a person's change in stress or anxiety given exposure to natural scenes (e.g., Hartig et al. 2003) or, alternatively, a binary expression of states, such as whether or not a person shows an allergic response to specific stimulants (e.g., Hanski et al. 2012). The appropriate time frame for measuring different responses varies, because the effects of nature on a person have the potential to be immediate or delayed or they may disappear over time. For example, health outcomes such as changes in the prevalence of cardiovascular disease in response to active engagement with green exercise are likely only to become apparent over very long time frames with repeated or consistent engagement with green space (Mitchell and Popham 2008). Other well-being responses (for example, relief from mental fatigue and subsequent feelings of restoration from exposure to nature) can be immediately elicited on exposure to nature (i.e., the response is acute) and as a consequence may only be measurable in the immediate short term (e.g., Hartig et al. 2003, Fuller et al. 2007).

The shape and scale of the dose–response curve

Dose–response studies that provide information on how individuals respond to exposure to nature, whether that be measured as duration, frequency, or quality (or some combination of these variables), will be central to developing minimum dose recommendations (Barton and Pretty 2010, Whitelaw 2012). In addition, studies that examine how the health of populations responds to different levels of nature quantity or quality will be important for informing green space provision guidelines and policies. In particular, the shape of the dose–response relationship between nature dose and health response will provide crucial information on how small changes in the environment or exposure to nature could influence people's health. For example, the presence of thresholds could provide some indication of a minimum level of green space cover that should be provided in cities.

Given the range of ways that nature dose and health response have been measured to date, in many instances, meta-analytical approaches to developing dose–response curves are impossible. However, there is evidence to indicate *a priori* what some of these curves might look like. Here, we review the evidence for some likely curve shapes, focusing on the health responses that have received the most attention in the scientific literature to date.

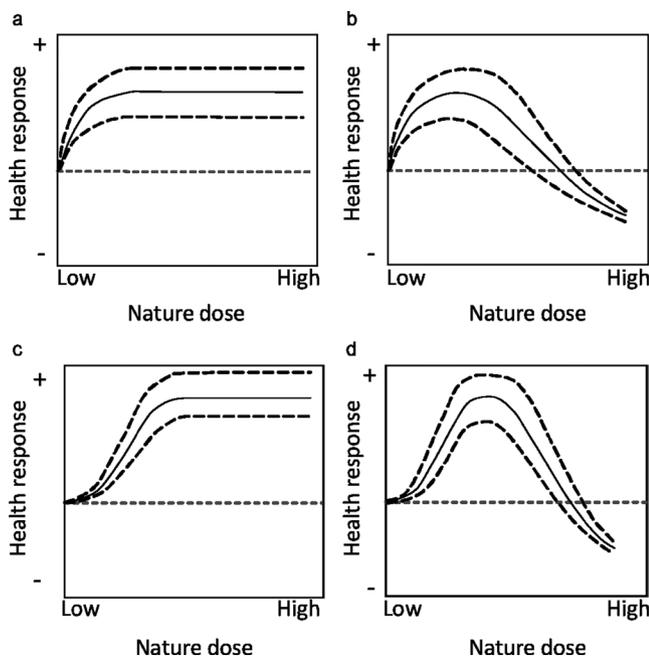


Figure 2. Possible forms for the relationship between nature dose and health response. The solid lines show the main trend, and the dashed lines indicate possible variations in scale of the health response.

A rapid improvement in health followed by a plateau or decline.

Studies that have examined the link between nature dose and psychological well-being at the individual level have variously measured all three components of exposure; this includes measures of quality (e.g., the effect of bird or plant species richness on reflection; Fuller et al. 2007) and quantity (e.g., the effect of landscapes with varying levels of natural features on stress; Beil and Hanes 2013), but the most common measure is the duration of exposure to nature. There is certainly evidence to suggest that a very rapid improvement in psychological well-being is possible in response to very low durations of nature dose, after which the rate of response could either plateau (figure 2a) or decline (figure 2b). For example, cognitive function has been found to improve after less than ten minutes of viewing photographs of natural settings (Berto 2005). Similarly, rapid responses to natural environments have been identified within studies that examine the effects of mere glimpses of nature from a window at home; these have been correlated with improved feelings of life satisfaction and well-being (Kaplan 2001). These studies on responses to both real nature and pictures also suggest that both passive (i.e., occasionally seeing nature through a home window) and active (i.e., active viewing of photographs or video) exposure to nature can elicit acute health responses with only very low durations of nature dose. Similarly, figure 1d illustrates how improvements in blood pressure can be achieved with very short periods of exposure to real natural settings (Hartig et al. 2003), and forest bathing experiments in Japan have also found rapid reductions in heart rate within

minutes of exposure to natural forest environments (Lee et al. 2011). These improvements are unlikely to continue at the same rapid rates as the nature dose increases even further. Certainly, Barton and Pretty (2010) found that five minutes of green exercise resulted in a greater rate of improvement in feelings of restoration and self-esteem than a full day of exposure, suggesting that the psychological well-being benefits do not increase linearly with time.

In general, a plateau in the rate of health improvement could be expected when increases in nature have little or no further impact on people or when increases in nature are no longer possible. This may particularly be the case when considering quantity of nature; for example, increasing “greenness” within a window view may have no additional effect once a particular threshold point is reached. A decline in well-being could occur when further increases in the measured element of nature have a detrimental impact on people. For example, although many studies have shown that natural landscapes enhance the psychological well-being of individuals (Kaplan and Kaplan 1989, Berman et al. 2012, Dallimer et al. 2012, Beil and Hanes 2013), the stress theory proposed by Ulrich (1983) suggests that increased complexity and crowding of vegetation (as a measure of nature quality) could decrease a person’s feeling of safety and increase stress. In addition, although the presence of water bodies can elicit a positive outcome for psychological well-being (White et al. 2013a), increasing levels of stagnant water in urban environments also provide breeding grounds for mosquitoes that transmit disease (Quiroga et al. 2013).

The relationship between temperature regulation and reduced heat-related illness could also show a rapid initial improvement followed by a plateau. Heat exposure has important implications for human health (O’Neill et al. 2009) and increased vegetation cover is considered an important strategy for reducing the urban heat island effect (Hardin and Jensen 2007, O’Neill et al. 2009) because it provides shade and reduces temperatures through evapotranspiration and heat reflection (Bolund and Hunhammar 1999, Hardin and Jensen 2007). While temperature-regulating effect of vegetation in response to increasing quantities of nature has received limited attention, the studies that do exist suggest there can be an immediate effect on temperature even at low levels of nature, where quantity is measured as tree cover (Lin et al. 2014). Depending on the nature variable measured, the level of improvement in temperature can then either slow (similar to the curve shape shown in figure 2a, as has been shown to be the case for tree cover; Lin et al. 2014) or continue linearly towards an upper limit, as is the case for the relationship between temperature and leaf area (Hardin and Jensen 2007). Although no study to date has explicitly linked the temperature regulation services that nature can provide to health outcomes, the shape of the relationship between measures of nature (such as tree cover) and heat-related illness prevalence may follow similar shapes when measured at the population scale. However, the relationship is likely to be complicated by a range of mitigating

factors, such as where vulnerable people are located within a city (Harlan et al. 2006), as well as the spatial arrangement of vegetation (Zhou et al. 2011).

A gradual increase in improvement in health followed by a plateau or decline. Another potential relationship between nature and health is a gradually increasing improvement in health followed by an eventual plateau (figure 2c) or decline (figure 2d). Mitchell and Popham (2008) provided an example in which only a gradual reduction in mortality from cardiovascular disease was observed for higher-income groups at low quantities of nature (measured as green space cover). However, as green space increased further, the rates of reduction in mortality also increased. This reduced mortality in greener neighborhoods could have been driven by higher levels of physical activity (Mitchell and Popham 2008) or improved air quality in a neighborhood as a result of air filtering by vegetation (Laden et al. 2006). Conversely, at the individual level, the rate of improvement in cardiovascular health may actually be quite rapid in response to increasing the duration of exposure to nature. Mao and colleagues (2012) found that measures of cardiovascular health in the elderly improved significantly over the course of a seven-day experiment, and Hartig and colleagues (2003) showed that blood pressure can be reduced over only short duration exposures to natural environments (see figure 1d). These results suggest that short-term, nature-based health interventions could be effective in enhancing health outcomes for individuals.

Conceptually, the reduction in mortalities from cardiovascular disease at the population level may plateau as nature increases further simply because at some point, no further benefits can be delivered and because the spatial constraints in urban environments mean that the area of public green space may never reach detrimental levels. However, a decline in this same health response (i.e., increased mortality from cardiovascular disease) is conceivable when increased tree cover raises the pollen load in the air beyond a tolerable threshold. This change has the potential to elicit an allergic response from a substantial proportion of the population, which, in turn, could lead to the increased prevalence of respiratory illnesses and cardiovascular disease (Bergmann and Sypniewska 2011).

Moderating factors that influence dose–response curves

The scale of health response that nature elicits from people, as well as the shape of the dose–response curve, will inevitably be influenced by a range of factors; this includes characteristics of the individual or individuals involved and the time frame of the study (Altshuler 1981), and for biophysical ecosystem services, the spatial arrangement of natural features in the landscape may also be important (Zhou et al. 2011). These factors have generally received little attention in studies on the health–nature link, and they create significant complexity when attempting to create dose–response curves (Whitelaw 2012); however, population-level studies

have shown that accounting for them can be crucial for detecting the sometimes trace effects of nature on health (Mitchell and Popham 2008, White et al. 2013b, Hartig et al. 2014).

Culture. Studies on the health–nature connection are geographically biased toward North America and Europe (Keniger et al. 2013), and so there is limited direct evidence on how culture influences the shape and scale of the dose–response relationship. Culture is likely to influence both nature provision (i.e., the quantity and quality of nature within a landscape) and whether a person actively seeks out nature experiences (i.e., the duration and frequency of nature dose). First, culture can determine nature provision through its influence on city form, landscape characteristics, and park and garden design, alongside other important drivers of green space availability, such as development history and population density (Kaplan and Kaplan 1989, Fuller and Gaston 2009, Trigger and Head 2010, Dallimer et al. 2011). At an individual level, culture can influence the amount of nature that a person is likely to be exposed to through its relationship with personal preferences and lifestyle. There is certainly strong evidence of the effect of ethnicity on attitudes toward and use of green space, as well as motivation for outdoor recreation (Ozguner 2011).

Socioeconomic advantage or disadvantage. Socioeconomic factors can influence the quantity and quality of nature in urban environments; for example, nature quality (e.g., plant diversity or native remnant vegetation cover) and quantity (e.g., percentage of tree cover in a neighborhood) have been found to be higher in more advantaged neighborhoods (Kirkpatrick et al. 2007, van Heezik et al. 2013, Shanahan et al. 2015). This could be due to greater available resources for greening activities or because unequal power relationships between communities and local governments can influence investment in public areas (Heynen et al. 2006). The net result of this pattern is that people who live in more advantaged areas might receive higher day-to-day doses of nature. Other studies have found that socioeconomic advantage or disadvantage, as well as demographic characteristics such as age and gender, can influence whether a person is likely to visit a park (i.e., the frequency and duration of nature dose). For example, Jones and colleagues (2009) found that whereas over 40% of people in the most advantaged socioeconomic group visited parks in Bristol, United Kingdom, only 27% of those in the least advantaged group did so. Such behavioral differences could contribute to people in more advantaged areas receiving higher doses of nature than those in less advantaged neighborhoods.

Personal preferences and knowledge. Personal preferences associated with nature and knowledge of nature are likely to be inextricably linked with both the nature dose that a person is exposed to and the scale of the health benefits

received. For example, a person's orientation toward nature has a greater influence on park visitation (i.e., nature dose) than the proximity of parks to the home (Lin et al. 2014), and personal preferences can influence the perceived restorativeness of a landscape (i.e., the health response; Wilkie and Stavridou 2013). A person's perception of biodiversity (such as their estimate of species richness) has also been found to have a greater correlation with well-being outcomes than actual measures of biodiversity (Dallimer et al. 2012). This suggests that knowledge of the environment might fundamentally influence the scale of benefits that people can receive from nature. Interestingly, this pattern does not necessarily always hold, because people who deal with natural resources on a day-to-day basis (e.g., forestry workers) may receive relatively low restorative benefits from walking in natural environments (von Lindern et al. 2013).

Demographic and physiological characteristics, psychological well-being. A wide range of physiological factors will influence whether a person displays a positive health response to changing doses of nature. For example, nature could provide little or no additional protection from cardiovascular diseases or high blood pressure for people who have a number of risk factors, which could include advanced age, a genetic predisposition, or diabetes (Haffner et al. 1998, Wilson et al. 1998, Yusuf et al. 2005). Conversely, nature could play a particularly important role when it provides protection against illnesses to which a person is particularly susceptible (e.g., the reduction in heat island effect provided by nature may be more important for the young and the elderly; O'Neill et al. 2009). Interestingly, the restoration and well-being benefits of nature may be greatest for individuals experiencing stress or anxiety, and if this holds true, the influence of nature or green exercise on psychological well-being will be much greater, with a more immediate rapid increase for more stressed individuals (Ulrich 1986, Barton and Pretty 2010). There is support for this hypothesis in that individuals who are more mentally fatigued have been found to anticipate greater restoration from spending time in natural environments (Hartig and Staats 2006).

Toward nature-based health interventions

Clearly, there is a great deal of complexity that will ultimately complicate the generation of dose-response curves for the nature-health connection. However, we see three key approaches that could be used to bridge this knowledge gap. First, population-level studies have demonstrated how an epidemiological approach can be employed statistically to account for a range of potentially complicating factors through multivariate regression (e.g., Mitchell and Popham 2008, White et al. 2013b). This approach, when well designed, can enable the researcher to discover what proportion of different populations (e.g., people from different socioeconomic brackets) responds to different levels of green cover, particularly when the effect size is small (Hartig

et al. 2014). Although this approach will not necessarily provide information on causality, it could be used both for identifying vulnerable populations and for spatial planning to reduce health inequalities.

Second, as highlighted in the temperature regulation example described in this article, examining the relationship between a measure of nature and a biophysical change in the environment provides a necessary intermediate step that could be used to predict at what point the best health benefits for a population might be achieved. This mechanistic approach to enhancing health benefits could be used to guide broadscale or neighborhood-scale recommendations for the proportion of green cover that should be present within cities. Importantly, such interventions could have multifaceted health outcomes for communities both immediately and in the longer term (Whitelaw 2012), and these additional benefits or disbenefits also need to be considered through the planning process.

The third approach that is likely to be particularly useful in generating dose response curves is experimental manipulations of exposure to nature at the individual scale, such as the example illustrated in figure 1d (Hartig et al. 2003). Studies that control for any potentially confounding factors (such as the subjectivity of nature experiences; Hartig et al. 2014) will be invaluable for demonstrating causality and moving the discipline beyond primarily correlative research. Barton and Pretty (2010) have already demonstrated how data from individual-level studies can be incorporated into a meta-analytical approach to identify appropriate doses of green exercise. Therefore, this will provide a key way through which minimum dose recommendations could be made.

Conclusions

A major consequence of continued urbanization is that more people will be exposed to the health risks associated with city living. Urban nature could provide a cost-effective tool to reduce these health risks, because there is a growing body of evidence showing it has links to improved physical, psychological, and social well-being. To operationalize these initiatives effectively, research is needed to develop a precise knowledge of the type and amount of nature required for specific health outcomes. Here, we have explored how dose-response modeling, an approach commonly used in the health sciences, could be employed to inform nature-based health interventions. We highlight that there are three important aspects of nature dose, including the quality and quantity of nature (i.e., the intensity) and the frequency and duration of exposure, and each of these aspects of nature dose are likely to be linked to different health responses in different ways, over different time frames, and at different scales. To date, the varying ways that nature dose and health response have been measured generally precludes meta-analytical approaches to examining dose-response relationships. This suggests that there is a crucial need to take a mechanistic approach to developing measures of nature dose

to understand how it might be manipulated to deliver better health outcomes (Hartig et al. 2014).

Here, we have also explored some of the factors that will inevitably influence the scale and shape of many dose–response curves. This complexity is one of the key reasons that the dose–response concept has been considered to hold limited utility in public health science (Whitelaw 2012). Despite these concerns, the concept can be used to simplify complex information for the public through minimum dose recommendations (Whitelaw 2012) and could also have significant utility for informing green space policy and planning guidelines. To this end, we have shown that there is sufficient evidence to develop *a priori* indications of what some dose–response relationships might look like for different health responses. However, a new research direction is now required to generate quantifiable nature-based health recommendations. This requires a much closer collaboration among health scientists, ecologists, and sociologists and should include a mechanistic examination of nature–health links.

Acknowledgments

DFS is supported through Australian Research Council (ARC) Discovery Grant no. DP120102857; RAF holds an ARC Future Fellowship; BBL is supported through the Commonwealth Scientific and Industrial Research Organisation Climate Adaptation Flagship; and KJG is supported by United Kingdom's Natural Environment Research Council grant no. NE/J015237/1. This research is also supported by the Australian National Environmental Research Program.

References cited

- Altshuler B. 1981. Modeling of dose–response relationships. *Environmental Health Perspectives* 42: 23–27.
- Barton J, Pretty J. 2010. What is the best dose of nature and green exercise for improving mental health? A multi-study analysis. *Environmental Science and Technology* 44: 3947–3955.
- Beil K, Hanes D. 2013. The influence of urban natural and built environments on physiological and psychological measures of stress: A pilot study. *International Journal of Environmental Research and Public Health* 10: 1250–1267.
- Bergmann K, Sypniewska G. 2011. Is there an association of allergy and cardiovascular disease? *Biochimica Medica* 21: 210–218.
- Berman MG, Jonides J, Kaplan S. 2008. The cognitive benefits of interacting with nature. *Psychological Science* 19: 1207–1212.
- Berman MG, Kross E, Krpan KM, Askren MK, Burson A, Deldin PJ, Kaplan S, Sherdell L, Gotlib IH, Jonides J. 2012. Interacting with nature improves cognition and affect for individuals with depression. *Journal of Affective Disorders* 140: 300–305.
- Berto R. 2005. Exposure to restorative environments helps restore attentional capacity. *Journal of Environmental Psychology* 25: 249–259.
- Bird WJ. 2004. Natural Fit: Can Green Space and Biodiversity Increase Levels of Physical Activity? Royal Society for the Protection of Birds.
- Bolund P, Hunhammar S. 1999. Ecosystem services in urban areas. *Ecological Economics* 29: 293–301.
- Dallimer M, Tang ZY, Bibby PR, Brindley P, Gaston KJ, Davies ZG. 2011. Temporal changes in greenspace in a highly urbanized region. *Biology Letters* 7: 763–766.
- Dallimer M, Irvine KN, Skinner AMJ, Davies ZG, Rouquette JR, Maltby LL, Warren PH, Armsworth PR, Gaston KJ. 2012. Biodiversity and the feel-good factor: Understanding associations between self-reported human well-being and species richness. *BioScience* 62: 47–55.
- De Vries S, van Dillen SME, Groenewegen PP, Spreeuwenberg P. 2013. Streetscape greenery and health: Stress, social cohesion and physical activity as mediators. *Social Science and Medicine* 94: 26–33.
- Donovan GH, Butry DT, Michael YL, Prestemon JP, Liebhold AM, Gatzliolis D, Mao MY. 2013. The relationship between trees and human health evidence from the spread of the emerald ash borer. *American Journal of Preventive Medicine* 44: 139–145.
- Dye C. 2008. Health and urban living. *Science* 319: 766–769.
- Frumkin H. 2003. Healthy places: Exploring the evidence. *American Journal of Public Health* 93: 1451–1456.
- Fuller RA, Gaston KJ. 2009. The scaling of green space coverage in European cities. *Biology Letters* 5: 352–355.
- Fuller RA, Irvine KN, Devine-Wright P, Warren PH, Gaston KJ. 2007. Psychological benefits of greenspace increase with biodiversity. *Biology Letters* 3: 390–394.
- Groenewegen PP, van den Berg AE, Maas J, Verheij RA, de Vries S. 2012. Is a green residential environment better for health? If so, why? *Annals of the Association of American Geographers* 102: 996–1003.
- Haffner SM, Lehto S, Ronnema T, Pyorala K, Laakso M. 1998. Mortality from coronary heart disease in subjects with type 2 diabetes and in nondiabetic subjects with and without prior myocardial infarction. *New England Journal of Medicine* 339: 229–234.
- Han K. 2009. Influence of limitedly visible leafy indoor plants on the psychology, behaviour, and health of students at a junior high school in Taiwan. *Environment and Behaviour* 41: 658–692.
- Hanski I, et al. 2012. Environmental biodiversity, human microbiota, and allergy are interrelated. *Proceedings of the National Academy of Sciences* 109: 8334–8339.
- Hardin PJ, Jensen RR. 2007. The effect of urban leaf area on summertime urban surface kinetic temperatures: A Terre Haute case study. *Urban Forestry and Urban Greening* 6: 63–72.
- Harlan SL, Brazel AJ, Prashad L, Stefanov WL, Larsen L. 2006. Neighborhood microclimates and vulnerability to heat stress. *Social Science and Medicine* 63: 2847–2863.
- Hartig T, Staats H. 2006. The need for psychological restoration as a determinant of environmental preferences. *Journal of Environmental Psychology* 26: 215–226.
- Hartig T, Mang M, Evans GW. 1991. Restorative effects of natural environment experiences. *Environment and Behavior* 23: 3–26.
- Hartig T, Mitchell R, de Vries S, Frumkin H. 2014. Nature and health. *Annual Review of Public Health* 35: 207–228.
- Hartig T, Evans GW, Jamner LD, Davis DS, Gärling T. 2003. Tracking restoration in natural and urban field settings. *Journal of Environmental Psychology* 23: 109–123.
- Haskell WL, Lee IM, Pate RR, Powell KE, Blair SN, Franklin BA, Macera CA, Heath GW, Thompson PD, Bauman A. 2007. Physical activity and public health: Updated recommendation for adults from the American College of Sports Medicine and the American Heart Association. *Medicine and Science in Sports and Exercise* 39: 1423–1434.
- Heynen N, Perkins HA, Roy P. 2006. The political ecology of uneven urban green space: The impact of political economy on race and ethnicity in producing environmental inequality in Milwaukee. *Urban Affairs Review* 42: 3–25.
- Hough RL. 2014. Biodiversity and human health: Evidence for causality? *Biodiversity and Conservation* 23: 267–288.
- Humpel N, Owen N, Leslie E. 2002. Environmental factors associated with adults' participation in physical activity: A review. *American Journal of Preventive Medicine* 22: 188–199.
- Jackson LE, Daniel J, McCorkle B, Sears A, Bush KF. 2013. Linking ecosystem services and human health: The Eco-Health Relationship Browser. *International Journal of Public Health* 58: 747–755.

- Jones A, Hillsdon M, Coombes E. 2009. Greenspace access, use, and physical activity: Understanding the effects of area deprivation. *Preventive Medicine* 49: 500–505.
- Kaczynski AT, Henderson KA. 2007. Environmental correlates of physical activity: A review of evidence about parks and recreation. *Leisure Sciences* 29: 315–354.
- Kaplan R. 2001. The nature of the view from home: Psychological benefits. *Environment and Behaviour* 33: 507–542.
- Kaplan R, Kaplan S. 1989. *The Experience of Nature: A Psychological Perspective*. Cambridge University Press.
- Keniger LE, Gaston KJ, Irvine KN, Fuller RA. 2013. What are the benefits of interacting with nature? *International Journal of Environmental Research and Public Health* 10: 913–935.
- Kirkpatrick JB, Daniels GD, Zagorski T. 2007. Explaining variation in front gardens between suburbs of Hobart, Tasmania, Australia. *Landscape and Urban Planning* 79: 314–322.
- Kriebel D, Checkoway H, Pearce N. 2007. Exposure and dose modelling in occupational epidemiology. *Occupational and Environmental Medicine* 64: 492–498.
- Lachowycz K, Jones A. 2012. Towards a better understanding of the relationship between greenspace and health: Development of a theoretical framework. *Landscape and Urban Planning* 118: 62–69.
- Laden F, Schwartz J, Speizer FE, Dockery DW. 2006. Reduction in fine particulate air pollution and mortality: Extended follow-up of the Harvard six cities study. *American Journal of Respiratory and Critical Care Medicine* 173: 667–672.
- Lee C, Ory MG, Yoon J, Forjuoh SN. 2013. Neighborhood walking among overweight and obese adults: Age variations in barriers and motivators. *Journal of Community Health* 38: 12–22.
- Lee J, Park BJ, Tsunetsugu Y, Ohira T, Kagawa T, Miyazaki Y. 2011. Effect of forest bathing on physiological and psychological responses in young Japanese male subjects. *Public Health* 125: 93–100.
- Lin BB, Fuller RA, Bush R, Gaston KJ, Shanahan DF. 2014. Opportunity or orientation? Who uses parks and why. *PLOS ONE* 9 (art. e87422).
- Lin BB, Meyers J, Barnett G. 2014. Urban densification and green space trade-offs for climate regulation in Sydney, Australia. Conference presentation to 99th ESA Annual Convention 2014.
- Lovasi GS, Quinn JW, Neckerman KM, Perzanowski MS, Rundle A. 2008. Children living in areas with more street trees have lower prevalence of asthma. *Journal of Epidemiology and Community Health* 62: 647–649.
- Maas J, Verheij RA, Groenewegen PP, de Vries S, Spreeuwenberg P. 2006. Green space, urbanity, and health: How strong is the relation? *Journal of Epidemiology and Community Health* 60: 587–592.
- MacKerron G, Mourato S. 2013. Happiness is greater in natural environments. *Global Environmental Change—Human and Policy Dimensions* 23: 992–1000.
- Mao GX, Cao YB, Lan XG, He ZH, Chen ZM, Wang YZ, Hu XL, Lv YD, Wang GF, Yan J. 2012. Therapeutic effect of forest bathing on human hypertension in the elderly. *Journal of Cardiology* 60: 495–502.
- Mitchell R. 2013. Is physical activity in natural environments better for mental health than physical activity in other environments? *Social Science and Medicine* 91: 130–134.
- Mitchell R, Popham F. 2008. Effect of exposure to natural environment on health inequalities: An observational population study. *The Lancet* 372: 1655–1660.
- O'Neill MS, Carter R, Kish JK, Gronlund CJ, White-Newsome JL, Manarolla X, Zanobetti A, Schwartz JD. 2009. Preventing heat-related morbidity and mortality: New approaches in a changing climate. *Maturitas* 64: 98–103.
- Ozguner H. 2011. Cultural differences in attitudes towards urban parks and green spaces. *Landscape Research* 36: 599–620.
- Powell KE, Paluch AE, Blair SN. 2011. Physical activity for health: What kind? How much? How intense? On top of what? *Annual Review of Public Health* 32: 349–365.
- Pretty J, Peacock J, Sellens M, Griffin M. 2005. The mental and physical health outcomes of green exercise. *International Journal of Environmental Health Research* 15: 319–337.
- Quiroga L, Fischer S, Schweigmann N. 2013. Immature mosquitoes associated with urban parklands: Implications for water and mosquito management. *Journal of the American Mosquito Control Association* 29: 27–32.
- Ratcliffe E, Gatersleben B, Sowden PT. 2013. Bird sounds and their contributions to perceived attention restoration and stress recovery. *Journal of Environmental Psychology* 36: 221–228.
- Richardson E[A], Pearce J, Mitchell R, Day P, Kingham S. 2010. The association between green space and cause-specific mortality in urban New Zealand: An ecological analysis of green space utility. *BMC Public Health* 10: 240.
- Richardson EA, Mitchell R, Hartig T, de Vries S, Astell-Burt T, Frumkin H. 2012. Green cities and health: A question of scale? *Journal of Epidemiology and Community Health* 66: 160–165.
- Richardson EA, Pearce J, Mitchell R, Kingham S. 2013. Role of physical activity in the relationship between urban green space and health. *Public Health* 127: 318–324.
- Shanahan DF, Lin BB, Gaston K, Bush R, Fuller RA. 2014. Socio-economic inequalities in access to nature on public and private lands: A case study from Brisbane, Australia. *Landscape and Urban Planning* 130: 14–23.
- Shanahan DF, Lin BB, Bush R, Gaston KJ, Barber L, Dean J, Fuller, RA. 2015. Pathways to health benefits from urban nature. *American Journal of Public Health* 105: 470–477.
- Smith TJ. 1992. Occupational exposure and dose over time: Limitations of cumulative exposure. *American Journal of Industrial Medicine* 21: 35–51.
- Tennessen CM, Cimprich B. 1995. Views to nature: Effects on attention. *Journal of Environmental Psychology* 15: 77–85.
- Timperio A, Giles-Corti B, Crawford D, Andrianopoulos N, Ball K, Salmon J, Hume C. 2008. Features of public open spaces and physical activity among children: Findings from the CLAN study. *Preventive Medicine* 47: 514–518.
- Tratalos J, Fuller RA, Warren PH, Davies RG, Gaston KJ. 2007. Urban form, biodiversity potential and ecosystem services. *Landscape and Urban Planning* 83: 308–317.
- Trigger DS, Head L. 2010. Restored nature, familiar culture: Contesting visions for preferred environments in Australian cities. *Nature + Culture* 5: 231–250.
- Turner WR, Nakamura T, Dinetti M. 2004. Global urbanization and the separation of humans from nature. *BioScience* 54: 585–590.
- Tzoulas K, Korpela K, Venn S, Yli-Pelkonen V, Kazmierczak A, Niemela J, James P. 2007. Promoting ecosystem and human health in urban areas using green infrastructure: A literature review. *Landscape and Urban Planning* 81: 167–178.
- Ulrich RS. 1983. Aesthetic and affective response to natural environment. Pages 85–125 in Altman I, Wohlwill JF, eds. *Behavior and the Natural Environment*. Plenum Press.
- . 1984. View through a window may influence recovery from surgery. *Science* 224: 420–421.
- . 1986. Human responses to vegetation and landscapes. *Landscape and Urban Planning* 13: 29–44.
- US Department of Agriculture, US Department of Health and Human Services. 2010. *Dietary Guidelines for Americans 2010*. US Government Printing Office.
- Van den Berg AE, Custers MHG. 2011. Gardening promotes neuroendocrine and affective restoration from stress. *Journal of Health Psychology* 16: 3–11.
- Van Heezik Y, Freeman C, Porter S, Dickinson KJM. 2013. Garden size, householder knowledge, and socio-economic status influence plant and bird diversity at the scale of individual gardens. *Ecosystems* 16: 1442–1454.
- Von Lindern E, Bauer N, Frick J, Hunziker M, Hartig T. 2013. Occupational engagement as a constraint on restoration during leisure time in forest settings. *Landscape and Urban Planning* 118: 90–97.
- White MP, Alcock I, Wheeler BW, Depledge MH. 2013a. Coastal proximity, health and well-being: Results from a longitudinal panel survey. *Health and Place* 23: 97–103.

- . 2013b. Would you be happier living in a greener urban area? A fixed-effects analysis of panel data. *Psychological Science* 24: 920–928.
- Whitelaw S. 2012. The emergence of a “dose–response” analogy in the health improvement domain of public health: A critical review. *Critical Public Health* 22: 427–440.
- Wilkie S, Stavridou A. 2013. Influence of environmental preference and environment type congruence on judgments of restoration potential. *Urban Forestry and Urban Greening* 12: 163–170.
- Wilson PWF, D’Agostino RB, Levy D, Belanger AM, Silbershatz H, Kannel WB. 1998. Prediction of coronary heart disease using risk factor categories. *Circulation* 97: 1837–1847.
- Wolfe MK, Mennis J. 2012. Does vegetation encourage or suppress urban crime? Evidence from Philadelphia, PA. *Landscape and Urban Planning* 108: 112–122.
- World Health Organization. 2013. Urban Population Growth, Global Health Observatory Database. World Health Organization. (14 February 2014; www.who.int/gho/urban_health/situation_trends/urban_population_growth_text/en/index.html)
- Yusuf S, et al. 2005. Obesity and the risk of myocardial infarction in 27,000 participants from 52 countries: A case-control study. *Lancet* 366: 1640–1649.
- Zhou WQ, Huang GL, Cadenasso ML. 2011. Does spatial configuration matter? Understanding the effects of land cover pattern on land surface temperature in urban landscapes. *Landscape and Urban Planning* 102: 54–63.

Danielle F. Shanahan (danielleshanahan@gmail.com) and Richard A. Fuller are affiliated with the School of Biological Sciences at the University of Queensland, Brisbane, Queensland, Australia. Robert Bush is affiliated with the School of Public Health, University of Queensland, Brisbane, Queensland, Australia. Brenda B. Lin is affiliated with the Australian Commonwealth Scientific and Industrial Research Organisation (CSIRO) Land and Water Flagship, in Aspendale, Victoria, Australia. Kevin J. Gaston is affiliated with the Environment and Sustainability Institute, at the University of Exeter, in Penryn, Cornwall, United Kingdom.