

# The impact of green space and biodiversity on health

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Urban green spaces are associated with many health outcomes, but the mechanisms underlying these links remain unclear. One explanation is that biodiverse microbiomes in green spaces affect human health by modifying immune function. Our systematic review included studies that investigated the relationship between green space and either health or biodiversity. Reported effects of green space on health were generally positive, but 22% of the papers identified either no effect or negative effects. We also found that although green space was commonly associated with biodiversity, few green-space health studies simultaneously examined biodiversity. Overreliance on cross-sectional studies, various definitions of green space, and a lack of research in tropical and developing nations limit the conclusions that can be drawn. A better understanding of the biological aspects of contact with nature is required before city planners can optimize green spaces for health gains.

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The patterns of human exposure to nature have changed markedly over the past several decades, due principally to rapid urbanization. Seventy percent of the world's population resided in rural areas in the 1950s, but this fraction will shift to urban settings by 2050, and relocation to cities is occurring most rapidly in developing countries (UN 2014). In many cities, densely packed high-rise buildings dominate, and little room remains for native flora or fauna (Gifford 2007). The competition for urban space results in a lack of exposure to natural environments (which we broadly refer to here as “green space”), and the implications for human health may be substantial.

## In a nutshell:

- Today's rapidly urbanizing population is quickly losing access to green space and biodiversity
- Of the studies included in our review, 78% reported positive correlations between green space interaction and mental and physical health (the most frequently reported gains applied to mental health); only 5% reported negative associations
- Exposure to diverse microorganisms may help explain the effects of urban green space, but few of the studies in our review investigated potential biological mechanisms
- It is unclear to what extent research conducted to date may be generalized to tropical and developing countries; existing knowledge gaps must be filled to support effective green space planning in rapidly urbanizing non-Western settings

Green spaces, as we have defined them, include many different habitats (Figure 1; Aronson *et al.* 2017), ranging from forests, conserved areas, parks, gardens, yards, and remnant patches of native vegetation to patches of vegetation within assemblages of modern or historically built environments. Green spaces contribute to the quality of urban life by providing basic ecosystem services such as air filtration, microclimate regulation, noise reduction, stormwater drainage, and sewage treatment, as well as opportunities for recreation (Bolund and Hunhammar 1999). Reported benefits to health resulting from exposure to green spaces include physical fitness and social cohesion (Hartig *et al.* 2014), improved mental health (Gascon *et al.* 2015), and reduced mortality (Gascon *et al.* 2016). Several studies have also documented negative effects, such as respiratory allergies (Andrusaityte *et al.* 2016) and injury (Bortolini *et al.* 2016). Explanations for these effects include psychological factors, sunlight exposure, and opportunities for exercise, but none of these proposed mechanisms explain the myriad “green space health effects” and the occasionally contradictory outcomes. Until the full range of mechanisms by which green spaces affect human health is better understood, scientists cannot predict with confidence the impacts that adding or removing a green space from an urban environment will have on public health.

One possible explanation of green-space health benefits is provided by the biodiversity hypothesis (Rook 2013; Kuo 2015; von Hertzen *et al.* 2015), which proposes that exposure to diverse microbiomes (communities of microbes such as bacteria, fungi, and protozoans) helps train the immune system to accurately distinguish dangerous from helpful bacteria, and immune modulation of this kind may affect a wide variety of health outcomes including cancer, depression, allergies, and auto-immune diseases. Some microbiomes are associated with natural environments (ie soils, plants, water), and exposure to diverse “environmental microbiomes” may contribute to the variety of microorgan-

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**Figure 1.** Biodiversity in an urban green space and in a natural area. (a) Urban green spaces, such as San Mateo Central Park in California, often lack biodiversity, whereas (b) natural areas outside cities, like that shown on Bruny Island in Tasmania, Australia, support a greater diversity of plants and animals. Although intuitive, these differences are seldom quantified, and therefore the role of biodiversity in contributing to human health outcomes is rarely examined.

isms in the human body. It is argued that exposures of this kind may protect against allergies (Hanski *et al.* 2012; Roukolainen *et al.* 2015), asthma (Ege *et al.* 2011), and upper respiratory tract infections (Fujimura *et al.* 2014) via alterations in immune function (expressed by changed levels of the immunoglobulin E [IgE] antibody, inflammatory cytokines, and activated T cells). However, little is known about the role that green space plays in contributing to the human microbiome, or the factors contributing to the diversity of the microbiome in green spaces. Scholarly literature at present fails to shed light on the effects of urban development on biodiversity in existing green spaces, and what this may mean for human health (Nelson and Forbes 2014; Nielsen *et al.* 2014).

Our objectives here were to systematically review the peer-reviewed literature related to green space and public health to (1) summarize the components of mental and physical health affected by green space and the direction of the associated effects (eg positive, negative, neutral), (2) explore mechanisms proposed to account for green-space-related health benefits,

(3) examine the extent to which biodiversity has been considered as a component of health impacts, and (4) identify the most important existing gaps in knowledge that must be filled before urban planners can effectively design green spaces for the benefit of global urban health.

## ■ Methods

Our systematic review comprised four distinct stages: (1) identification, (2) screening, (3) eligibility assessment, and (4) summary and synthesis. These are discussed in turn below.

### Identification

To identify relevant abstracts for potential inclusion within our review, we searched PubMed ([www.ncbi.nlm.nih.gov/pubmed](http://www.ncbi.nlm.nih.gov/pubmed)) for articles published between January 2007 and March 2017 using a strategy developed from systematic testing (WebTable 1).

### Screening

All abstracts were classified according to the following screening questions: (1) is “green space in urban area” one of the major research questions; (2) does the abstract relate to public health and green space; (3) does the abstract relate to biodiversity and green space; (4) what is the direction of evidence on green space and public health; and (5) what is the direction of evidence on biodiversity and public health? Other information considered in the screening process included study design, sample size, population, outcomes, green space variables, and the strength of associations.

### Eligibility assessment

To improve interpretations of the abstracts and reduce misclassification errors, we sorted the abstracts according to how they related to the screening questions. Abstracts were divided into two groups based on answers to the questions about relevance to green space and public health (GSH) and to green space, health, and biodiversity (GSHB). Two additional groups of abstracts that were not directly related to public health, referred to as green space and biodiversity (GSB) and green space (GS) (WebPanel 1), were classified but excluded in the summary and synthesis stage. Full-text manuscripts were retrieved for papers in all four groups; abstracts that were not relevant to urban green space were excluded from the present review.

### Summary and synthesis

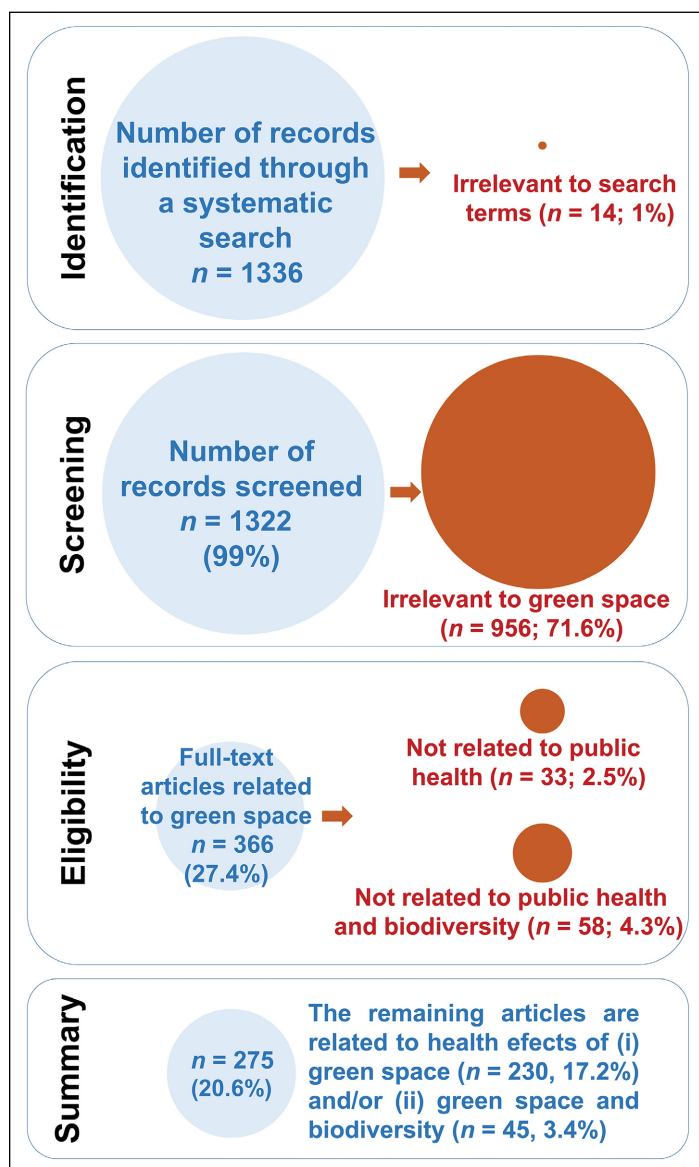
To provide quantitative and qualitative information on the scope of the screened literature (described above), we summarized all papers based on study design, topic, directions of health effect, categories of health outcomes, and the plausible biomedical and biodiversity mechanisms. We also identified evident research gaps relating to green space and

public health, and highlighted studies that included a component on biodiversity.

## Results

As of 7 Jun 2017, 1336 abstracts were identified through our systematic search (WebTable 2). About 72% of the returned abstracts were not relevant to green space, indicating the false positive rate of the search strategy (Figure 2); in total, 275 of the 1336 abstracts (20.6%) were relevant to our topic (the health effects of green space and biodiversity) and therefore examined more closely.

Of the papers that explored connections between green space and public health ( $n = 230$ ), almost all applied epidemiological



**Figure 2.** Search strategy and papers included and excluded (number and percent) at each stage. More details are available in WebPanel 1; a complete list of the papers and their classification is provided in WebTable 2. Size of each circle is relative to  $n$ .

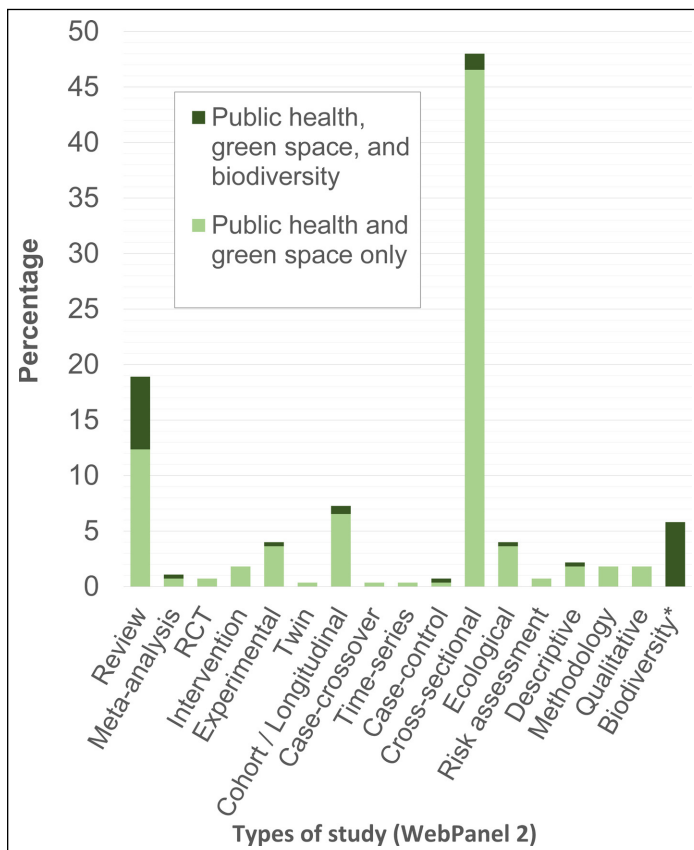
methods (WebPanel 2), and roughly two-thirds were observational studies (Figure 3). Some observational studies ( $n = 21$ ) used cohort, longitudinal, case-crossover, and time-series study designs, whereas others ( $n = 17$ ) included randomized controlled trials, intervention, or experimental approaches. The papers that examined biodiversity in addition to green space and health ( $n = 45$ ) were mostly reviews, and constituted what we describe as “biodiversity” studies (observational studies of biodiversity in urban green spaces with commentary on relevant health effects). Many of these studies focused on biodiversity or green space in association with either a natural agent (eg wild birds, wild boars, proteobacteria, arthropods [including ticks], bioaerosols, pollen) or an anthropogenic agent (eg dust, particulate pollutants, food waste). Health outcomes included lung cancer, cardiorespiratory disease, mental health, allergies, and immune system disorders (WebPanel 1). Overall, in the reviewed papers, cross-sectional studies were the most common category of research (48%), followed by reviews (19%) and cohort/longitudinal studies (7%) (Figure 3).

Most quantitative studies of the health effects of green space ( $n = 173$ , 87%) reported protective effects (Figure 4). Five studies (2.5%) demonstrated both positive and negative effects on perceived health (Mitchell and Popham 2007), obesity (Dadvand *et al.* 2014; Burgoine *et al.* 2015), and allergies (Dadvand *et al.* 2014; Fuertes *et al.* 2014; Carlsten and Rider 2017). One (0.5%) found optimal protective effects on mental health following moderate exposure to green space (Astell-Burt *et al.* 2014a); 14 studies (7%) did not show significant statistical associations between health and green space; and six studies (3%) described negative associations, including increases in mortality risk (Richardson *et al.* 2012), skin cancer (Astell-Burt *et al.* 2014b) and overall cancer risk (Zhang *et al.* 2016), asthma (Andrusaityte *et al.* 2016), and injury (Bortolini *et al.* 2016), as well as a reduction in physical-activity-based commuting (Maki-Opas *et al.* 2016). The most commonly reported clinical outcomes were mental, neurological, and behavioral (20%), while the most common non-clinical outcome was physical activity (18%; WebTable 3). Other frequently reported outcomes were obesity/overweight (9%) and self-perceived health (8%), followed by mortality (6%), cardiovascular health (5%), and metabolic health (4%).

Several review papers (WebTable 4) have hypothesized that exposure to microbial biodiversity may benefit immunoregulatory functions (Rook 2013; Rook *et al.* 2014), and that transmission of pathogens may occur less rapidly in biologically complex green areas (Rook *et al.* 2014). One cross-sectional study (Ruokolainen *et al.* 2015) concluded that microbial biodiversity was a plausible explanation for associations observed between green space and health, and another study (Wolf *et al.* 2017) experimentally connected microbial diversity to mental health. We found no experimental studies that focused on microbial biodiversity and physical health outcomes.

The papers reviewed offer mechanisms to explain green space effects, including cognitive restoration, stress reduction,





**Figure 3.** The proportion of abstracts ( $n = 275$ ) according to epidemiological study design and classification (WebPanel 2). The asterisk indicates the exception of papers using methods for studying non-human species rather than using epidemiological methods. RCT = randomized controlled trial.

low levels of air pollution, microclimate regulation, and promotion of physical activity and social interaction (WebTable 4). Two studies (Astell-Burt *et al.* 2014c; Halonen *et al.* 2014) proposed that other mechanisms could account for the direct health effects of green space besides those affecting lifestyle choices. Two intervention studies (Aspinall *et al.* 2015; South *et al.* 2015) specifically tested cognitive restoration and stress response mechanisms.

Evidence of health effects was demonstrated in studies in 23 different countries (WebPanel 1), most of which were highly developed Western nations (with a Human Development Index [HDI]  $\geq 0.80$ ); no studies exploring the green space health effects were found for medium developed (HDI: 0.55–0.7) or less developed (HDI  $< 0.55$ ) countries, and very few studies focused on countries in Africa, Asia, and Central and South America.

## Discussion

The number of papers exploring connections between human health and green space or between human health and biodiversity has multiplied in recent years, stimulated in part

by the paired rise in urban populations and certain chronic inflammatory diseases. In general, the health of urban residents is positively related to exposure to green space, but this relationship is not universal and there are occasionally negative effects. The results of recent studies focusing on the characteristics of health-advancing green space suggest that local biodiversity – and particularly microbial diversity – may be an important factor; however, we did not identify any experimental or intervention studies that tested this hypothesis directly.

## The health effects of green space

The health outcomes most often examined with respect to green space, and the ones examined with greatest rigor, are mental/neurological/emotional health effects and levels of physical activity (WebTable 3). For these categories, there are relatively clear and intuitive links to green space. Most studies are correlative or observational (cross-sectional, ecological) but several probed more deeply, exploring mechanistic connections; for example, one study found that green space positively impacted cognition by altering brain-wave patterns (Aspinall *et al.* 2015), whereas another demonstrated positive effects of green space due to reduced exposure to traffic-induced air pollution (Dadvand *et al.* 2015). Promotion of physical activity and social interaction by green space (Triguero-Mas *et al.* 2015) has been shown to reduce perceived stress levels, as well as to modify relevant physiological variables like heart rate (South *et al.* 2015).

Almost 90% of the associations between green space and health identified in our literature review were positive (that is, exposure to green space was linked with health gain). Only 5% of the studies showed negative impacts of green space interaction (Figure 4). In some instances, green space had both positive and negative effects, such as with allergies (Dadvand *et al.* 2014; Fuertes *et al.* 2014; Carlsten and Rider 2017), obesity (Dadvand *et al.* 2014; Burgoine *et al.* 2015), and mortality (Richardson *et al.* 2012; Gascon *et al.* 2016).

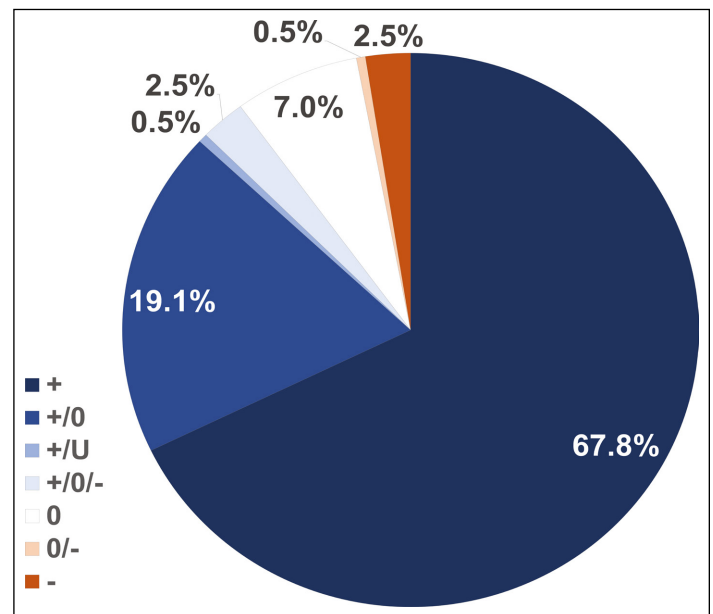
## Inter-study discrepancies

One possible explanation for conflicting positive and negative health effects is that the characteristics of green space differ from one study to another. Wheeler *et al.* (2015), for instance, reported that (apart from the estuaries land-cover type) certain types of forests, agricultural lands, grasslands, and coastal lands were positively associated with the prevalence of good health and negatively associated with self-reported bad health in census data. In the papers considered in our review, some included many forms of urban green space (eg parks, lawns, golf courses, woodlands, wetlands, other vegetated areas; Richardson *et al.* 2012), whereas others were more limited, including for example forest and agricultural lands but not parks and grasslands (Ruokolainen *et al.* 2015).

Other explanations for the variety of findings include unmeasured factors such as size and connectivity of urban green space (Lepczyk *et al.* 2017), human land-use patterns and development (Nelson and Forbes 2014), and the varying scales of the analyses (Richardson *et al.* 2012; Demuzere *et al.* 2014; Gascon *et al.* 2016). Some other potentially relevant biotic attributes of green space are rarely measured, such as the presence of invasive species as habitat homogenizing agents (Qian and Ricklefs 2007), the volume of understory habitats (Threlfall *et al.* 2017), and, notably, the level and composition of biodiversity. Moreover, green space was reported at widely different spatial resolutions, ranging from 5 m (Dadvand *et al.* 2015) to almost 10 km (WebPanel 1). Many studies used the normalized difference vegetation index (NDVI) (eg Dadvand *et al.* 2014, 2015; Triguero-Mas *et al.* 2015) to grade green spaces, while others relied on measures such as the leaf area index (Piao *et al.* 2015) or land-cover classifications (Richardson *et al.* 2012). This lack of a standardized approach to characterizing green space complicates direct comparisons between studies and understanding contradictory effects on health. If specific green space characteristics such as biodiversity, size, or connectivity can be directly tied to health metrics, then green space quality can be reported in a comparable fashion across studies, the results of which could be used to inform policy on how best to incorporate green space into urban design (Flies *et al.* 2017).

### The role of biodiversity

Our review suggests that biodiversity plays a key role in the green space–health connection, but clear evidence of this relationship is lacking in the scientific literature. To date, most of the papers that have focused on the role of biodiversity or included a biodiversity component are commentaries and thought pieces (Figure 3). There are exceptions, however. One cross-sectional study of children demonstrated a relationship between green space, skin microbial biodiversity, and allergic sensitization (when the immune system is primed so that even minor exposure to an otherwise harmless substance leads to an allergic reaction) (Ruokolainen *et al.* 2015). Green space was associated with greater microbial diversity on the skin and reduced levels of allergic disease. However, this particular study excluded parks and grasslands in its classification of “green space”, and it would be worth extending this research to include the types of green space that urbanites are most likely to be exposed to. Two other studies found associations between biodiversity and health, although it is unclear what the underlying mechanisms might be (Donovan *et al.* 2013; Wheeler *et al.* 2015). These findings are consistent with the “biodiversity” and “old friends” hypotheses (Hanski *et al.* 2012; Rook *et al.* 2014; von Hertzen *et al.* 2015), which propose that a greater diversity of microbes, especially with regard to those with which humans have co-evolved (ie “old friends”), helps to train and modulate the human immune system.



**Figure 4.** Findings of papers exploring the health impacts of green space ( $n = 199$ ). Directions of association on health: + (positively associated,  $\alpha \leq 0.05$ ), – (negatively associated,  $\alpha \leq 0.05$ ), 0 (no association,  $\alpha > 0.05$ ), and U (patterns/indications of a U-shaped dose–response relationship,  $\alpha \leq 0.05$ ). Thirty-one studies were excluded because they lacked quantitative study designs (eg reviews; methodological or descriptive studies).

Most of the evidence for the relationship between biodiversity and health derives from epidemiological and clinical studies in other disciplines. For example, it is well established that children exposed to farm environments or farm animals (Riedler *et al.* 2001) are less likely to develop allergies or inflammatory conditions. Children who live on farms appear to be exposed to diverse environmental microbiomes, which reduce allergic and inflammatory responses (Ege *et al.* 2011). Animal studies provide some evidential support; for instance, microbial communities in mice (Cahenzli *et al.* 2013) and pigs (Mulder *et al.* 2009) are altered when these animals are raised in sterile settings (theoretically similar to developed urban environments), and they tend to have higher levels of inflammation and allergies. Green spaces potentially offer the urban equivalent of the microbial exposure that farms and animals provide.

The “old friends” and “biodiversity” hypotheses warrant further exploration in relation to urban green space health benefits. The rapidly developing fields of amplicon sequencing, metagenomics, and metabolomics are facilitating the functional and genetic characterization of environmental and human microbial communities. Pairing these fields with advanced immunology techniques will shed further light on the ways in which exposure to diverse microbiomes may influence human health.

As with green space, biodiversity can also be characterized in a variety of ways, with important implications. For

example, bird, mammal, and plant communities respond differently to land-use change, as does the functional versus genetic diversity of those communities (Flynn *et al.* 2009). As compared with genetic diversity, functional diversity is often more difficult to quantify but may represent a more important indicator; results from analyses of genetic diversity may also be inconsistent with those looking at functional diversity (Flynn *et al.* 2009). Information on microbial functional diversity should be incorporated into assessments of urban green space characteristics in order to detect whether and how microbial diversity relates to remotely detectable green space attributes like NDVI, leaf area index, and land-cover classifications.

### Research gaps and future directions

In addition to the lack of environmental microbiome–health studies testing the biodiversity hypothesis, we identified a number of other research gaps. Most studies included in our review were conducted in developed nations in temperate regions; clearly, studies are also needed in less developed nations, both because they are currently underrepresented and because these regions are experiencing the most rapid growth in urban populations. We suggest that it is important to understand how climate impacts the ways in which people interact with green spaces in tropical regions, and the consequent effects on human health. The highest rates of urbanization and population growth are expected to occur in sub-Saharan Africa over the next several decades (UN 2014), and therefore a better understanding of the potential for green spaces to buffer adverse effects of the rural-to-urban demographic shift could yield substantial public health returns.

While many of the studies in our sample included measurements of the *quantity* of green space, primarily obtained from satellite-derived data, few attempted to define green space *quality*, primarily because it is still unclear what characteristics of green space confer health benefits and therefore constitute factors relating to “quality”. Before green spaces can be effectively implemented to improve health, the important characteristics (eg biodiversity, complexity, scale, accessibility) of high-quality spaces need to be elucidated.

In the past there has been negligible cross-disciplinary research that knits biological science and public health together, yet multiple perspectives are required to explore the underlying mechanisms that explain the pathophysiological effects of human exposure to biodiversity. A joint public health–ecology–bioinformatics program of work could provide robust, evidence-based solutions for improving the quality of urban greening policies worldwide, a win–win strategy for both humans and nature.

### Conclusions

The scientific literature on urban green space and public health dates back at least to the 1960s, when a French

study drew attention to the protective effects of plants, acting – so it was claimed – through microbiological pathways and via interactions with sulfuric air pollution (Raymond 1963). Since that time, the field has grown to the extent that green space is now linked with more than 20 different categories of health outcomes. But the mechanisms connecting health to green space remain unclear. The biodiversity hypothesis potentially provides a mechanism and a unifying explanation for the diverse health benefits; although we found no direct tests of this hypothesis in the urban green space–health literature, evidence in its favor is mounting from such sources as animal models and epidemiological studies. Experimental studies, including community-level interventions, are needed to identify these mechanisms, including the role of exposure to the diversity of environmental microorganisms found in natural environments.

This systematic review helps define the most important gaps in this field of research and therefore where scientific effort could achieve the greatest gains. Once the mechanisms underlying green space health effects – along with the characteristics, scale, and biological composition of green space that influence human health and ecosystem function – have been identified, urban green spaces can be optimized for public health gains on a global scale.

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### ■ Supporting Information

Additional, web-only material may be found in the online version of this article at <http://onlinelibrary.wiley.com/doi/10.1002/fee.2077/suppinfo>



## FrontiersEcoPics

### Casual encounter?

**O**n the banks of Limoncocha Lake, in Amazonian Ecuador, *Megalomyrmex incisus* ants seemed indifferent to the presence of a large, colorful, spiny, nymphalid caterpillar *Catonephele acontius* devouring



the leaves of an *Alchornea glandulosa* sapling. This plant species secretes extra floral nectar through specialized glands at the base of its leaves. This secretion is considered an indirect defense mechanism because it can attract the natural enemies of herbivores, including ants (*Ecology* 1978; doi.org/10.2307/1938771). The presence of these typically soil-residing ants on *A glandulosa* saplings suggests that they don't forage exclusively at the leaf-litter layer level but that they also sometimes gather nectar from plants. Surprisingly, during these observations, *M incisus* never attacked the caterpillar. If two herbivores – ants and caterpillars – are both obtaining large amounts of nutrients from the plant, a few simple questions arise: who is favored in the long term, and how? Or was this just a chance encounter? What kind of chemical (ie cyanide typically secreted by this Euphorbiaceae plant) or other signals do these nymphalid caterpillars use to avoid or manipulate ants? This is important, given that, unlike some other caterpillar species (eg many lycaenids), they lack dorsal nectar organs that provide ants with sugary secretions – a known mutualism between certain caterpillars and ants, which, in turn, protects the plant from other herbivores. Finally, is this an ant–plant mutualism in the making, or an example of an ant cheating the system?

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