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A Review of Epidemiologic Studies on Greenness and Health: Updated Literature Through 2017

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Abstract

Purpose of review—Many studies suggest that exposure to natural vegetation, or greenness, may be beneficial for a variety of health outcomes. We summarize the recent research in this area.

Recent findings—We observed consistent and strong evidence of associations for higher greenness with improvements in birth weights and physical activity, as well as lower mortality rates. Recent studies also suggested that exposure to greenness may lower levels of depression and depressive symptoms. The evidence on greenness and cardiovascular health remains mixed. Findings are also inconsistent for greenness measures and asthma and allergies.

Summary—Our knowledge of the impacts of greenness on a wide variety of health outcomes continues to evolve. Future research should incorporate information on specific species and some qualities of natural greenness that might drive health outcomes, integrate exposure assessments that incorporate personal mobility into analyses, and include prospective designs to add to the growing evidence that nature exposure positively affects health.

Keywords

Greenness; Green Spaces; Built Environment; Health Benefits; Mental Health; Urbanization

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Compliance with Ethical Standards

Conflict of Interest

Kelvin Fong, Jaime E. Hart, and Peter James, declare that they have no conflict of interest.

Human and Animal Rights and Informed Consent

All reported studies/experiments with human or animal subjects performed by the authors have been previously published and complied with all applicable ethical standards (including the Helsinki declaration and its amendments, institutional/national research committee standards, and international/national/institutional guidelines).

Introduction

There has been increasing interest in how exposure to natural vegetation, or greenness, may benefit human health [1–3]. The *biophilia* hypothesis proposes that seeking out connections with other forms of life is an innate human trait [4], and spending time in nature has long been thought to have benefits for human health [5]. Although a number of theories exist, greenness is generally thought to affect health through the following domains: reducing harm (mitigating exposures to heat, noise, and air pollution), relieving mental and physiologic stress, and promoting healthful activities such as exercise and socializing [3].

We have previously reviewed the literature on greenness and health through January 2015 [1]. We found there was convincing evidence suggesting a positive association between greenness and physical activity, although few prospective studies were conducted. Although cross-sectional studies dominated the literature, eleven studies showed that higher levels of greenness exposure were associated with lower levels of obesity/overweight. Studies suggested greenness was protective against negative mental health outcomes, but again the majority of studies were cross-sectional. As for birth outcomes, there was consistent evidence that higher levels of greenness were linked to increased birth weight, while evidence for other outcomes was ambiguous. Fewer studies evaluated the relationship between greenness and cardiovascular disease, and the majority of these analyses demonstrated that higher greenness was related to lower levels of cardiovascular disease. These studies were limited by ecological or cross-sectional designs. Most studies examining greenness and mortality were ecological or limited by incomplete control for confounding. Nevertheless, these studies were consistent in their findings that mortality rates were lower in areas with higher levels of greenness. In this new review, we focus on studies published after January 2015.

Methods

We conducted a PubMed Advanced Search on October 15, 2017 for studies with titles or abstracts containing “greenness” or “green space” as the exposure. Search results were further limited to those studying humans only. Next, we screened titles and abstracts to select only those that conducted original primary research, excluding reviews and commentaries, and only included observational studies (experimental studies are outside of the scope of this review). The cut-off date for the earliest date of publication was January 22, 2015. This review is not meant to be comprehensive, but is intended to summarize recent literature on greenness and health. The main findings of each study are presented in a Supplemental Table 1.

Greenness Exposure Assessment

The most commonly-used metric to quantify greenness is the normalized difference vegetation index (NDVI), an index derived from satellite images. Chlorophyll in plants strongly absorbs visible light (0.4–0.7 μm) for photosynthesis, while leaves reflect near-infrared light (0.7–1.1 μm). NDVI calculates the ratio of the difference between the near-infrared region and red reflectance to the sum of these two measures [6]. NDVI ranges from −1 to 1, with more positive values representing higher quantities of vegetation. Most studies

used freely-available satellite-derived measurements of NDVI from agencies such as NASA. The most commonly used NDVI relied on Landsat images, which has a spatial resolution of 30 m, followed by NDVI from the Moderate Resolution Imaging Spectroradiometer (MODIS), which has only a 250 m spatial resolution but at higher temporal resolutions (i.e., every 16 days dating back to 2000) [7]. Some studies obtained NDVI at even finer spatial resolutions (e.g., 5 m) via satellites operated by private companies [8,9]. While more finely resolved data likely improves exposure accuracy, most studies that examined NDVI at different spatial buffers (ranging from 30m–1250m) did not find that associations varied by buffer size [10–17].

A limited number of studies have quantified exposure to green spaces (e.g., parks) using land cover datasets to assess, for instance, the proportion of parks in a participant's administrative boundary (e.g., Census tract) or within a given radius from the subject's address [13,15,16,18–24]. Other studies have assessed the road network distance between a participant's home address and green spaces such as parks, forests, agricultural land, and others [10,14,16,25–28]. Researchers have also used subjective perceptions of nature to assess greenness exposure. For instance, one study surveyed perceptions of greenness from residents who lived in the same neighborhood but were not those who were studied for the health outcome and derived an overall metric reflecting the neighborhood greenness [29]. Some researchers conducted analyses focusing specifically on trees, for instance by using land use datasets on tree cover [12,24,30] or the number of trees around a residential address based on a tree census [10].

Exposure to greenness is commonly defined at participants' home addresses based on a spatial dataset measuring greenness for the area around the residence. However, in addition to studies discussed in our past review [31], some recent studies incorporated data for multiple locations individuals visited throughout the day. In studies of schoolchildren in Spain, Dadvand and colleagues weighted greenness exposure by time spent awake at home, school, and commuting [8,32]. Other studies obtained high-resolution measures of location using global positioning systems (GPS) to understand exposure based on time-weighted locations the participants visited throughout the day. James and colleagues used GPS device data to ascertain greenness exposure every minute over the course of a week in participants across the United States [33].

When assessing the relationship between greenness and health, there is still uncertainty about the etiologically most relevant time window of exposure. For this reason, one study considered both short term (1, 3, 6 month) and long term (1, 2, 3 year) averages based on the NDVI [34]. Studies have also attempted to determine a most influential time windows such as for maternal exposures to greenness during pregnancy [35].

The field of exposure assessment in greenness and health is still evolving. Measures of NDVI, while well-established, do not provide information on the quality of natural spaces, nor do they detail species of trees or other vegetation. Using the residential address to determine exposure is another limitation of the literature as this approach ignores other locations where exposure to nature might occur. Future studies examining movement throughout the day will provide further insight into how individuals interact with nature, and

how those interactions are linked to health outcomes. Finally, more research is required on the relevant time windows for exposure to nature influencing different health endpoints.

Physical Activity

Increased greenness or proximity to green spaces is thought to promote physical activity by providing a setting for walking, running, cycling, and other exercise. Our previous review of a largely cross-sectional literature, concluded that higher levels of greenness were indeed associated with increased physical activity.

The recent literature of study that employed a number of designs further supports a positive relationship between greenness and physical activity. In three studies in which physical activity was objectively measured by hip-worn accelerometers [19,30,33], positive associations between greenness and physical activity were found, despite the fact that the studies processed accelerometry data in different ways [19,30,33]. For example, by analyzing the accelerometry counts in combination with temporally-matched GPS-based NDVI data, a recent US-based study investigated possible non-linearity in the overall positive association between greenness and physical activity. The authors found that from 0 to 0.4 NDVI, there was a linear increase that flattened from 0.4 to 0.7 but above 0.7 it increased again linearly with a higher slope [33]. Among the remaining studies, one found that those living in the highest quartile of NDVI were more likely to participate in leisure time physical activity measured through questionnaires [36]. Another study based in Montreal, Canada, found that the odds of reporting active transportation was lower with increased NDVI at the home, at the destination, and along the path of the commute after adjustment for transportation access, population density, socioeconomic status, commute distance, and area-level walking rates [37].

A few studies assessed physical activity through surveys. Of note, a cross-sectional study across the entire United Kingdom utilized high resolution NDVI data at 0.5 m resolution [9]. The authors found that among 333,183 adult participants, an IQR (0.24) increase in NDVI in the 500m area around a participant's home was associated with a 9.3% (95% CI: 8, 11) increase in the odds of using active travel (walking, cycling, or public transport) for non-work trips, as well as a 3.9% (95% CI: 3, 5) increase in the odds of walking for physical activity more than 30 minutes per day. A study of 69,910 adults in Canada similarly found that those residing in the highest quartile of greenness (500m buffer NDVI >0.436) had a 34% higher odds (95% CI: 1.25, 1.44) of participating in physical activity in their leisure time compared with those in the lowest quartile of greenness (NDVI <0.205) [36]. Another Canadian study observed the opposite. When researchers surveyed 37,165 Montreal residents on commute trip distances and walking/cycling speeds [37], they found that higher levels of NDVI around the commute origin and destination as well as along the commute path was associated with lower odds of active commuting (OR 0.59, 95% CI: 0.53, 0.66 per unit increase in NDVI) after adjustment for transportation access, population density, socioeconomic status, commute distance, and area-level walking rates. This was the only study reviewed that reported a negative association between greenness exposure and physical activity.

The recent literature builds on previous research and further confirms the generally strong link between greenness and physical activity. Studies using both self-report and objective methods have found that greenness was associated physical activity. Future studies should continue to use GPS-based measures of exposure assessment and objective measures of physical activity with longer periods of follow-up. One potential shortcoming of this literature is the potential for self-selection to explain findings, where individuals with healthier behaviors may choose to live in or spend time in greener areas [38]. Future studies might attempt to measure and adjust for these health preferences in analyses to build the evidence base on nature and physical activity. Finally, more specificity with regards to the quality of natural environments most amenable to physical activity would further this area of inquiry.

Mental Health

Mental health has recently become a major focus of greenness and health research, as some theories suggested that exposure to nature may provide opportunities for social engagement or may even have a direct effect through lowering of stress [2,3]. Our previous review concluded that the literature consistently supports a positive relationship between greenness and mental health even though it relied mainly on a large number of cross-sectional studies.

Since this review, several studies have further added to the body of evidence for a link between greenness and higher self-rated mental health [16,28,29]. In two studies, researchers found that those living in greener areas had lower levels of depressive symptoms and depression; however, findings were only observed for some but not all greenness measures [18,39]. For example, in a prospective study of individuals with diabetes, NDVI was associated with a lower risk of depression, however, density of parks/recreational space did not influence depression [39]. In another study of pregnant women in Bradford, United Kingdom, those who resided in the 3rd or higher quintiles of greenness were 18–23% less likely to report depressive symptoms [27]. Moreover, stronger effect for greenness were estimated among those who were disadvantaged and physically inactive. Researchers also investigated the relationship between greenness exposure and aggressive behavior in children assessed via a parental questionnaire [34]. A 0.12 increase in short-term (1 to 6 months) NDVI prior to questionnaire assessment was associated with a 0.4 decrease in aggressive behavior score (range: 0 to 39).

The recently published studies are in line with findings from our prior review that intermediate strength of evidence for the relationship between increased greenness and better mental health [1]. Future studies with improved exposure assessment to isolate specific features of the natural environment that might influence mental health are needed. Also, prospective designs would help to provide more evidence for a relationship between greenness and mental health.

Birth Outcomes

Maternal exposure to greenness is thought to affect birth outcomes via increasing physical activity, improving mental health, and buffering detrimental effects of air pollution, noise, and extreme heat exposures [1,40]. Prior research has built a strong case for a positive

association for greenness exposure and birth weight [1,40]. Findings are less consistent for other birth outcomes. Previous studies also suggest that associations between greenness and birth outcomes may be modified by socioeconomic status (SES), with stronger findings among participants of low SES.

Recently published research into greenness and birth outcomes has continued to focus on birth weight and related measures, i.e. low birth weight and small for gestational age. For instance, a large birth cohort study in Texas examined over 3 million births [35] and found that among full-term births, birth weight was higher when NDVI levels during pregnancies were higher. Those children born to mothers living in the greenest areas (NDVI >0.52) had, on average, a 1.9g (95% CI 0.1, 3.7) higher birth weight compared with those born to mothers who lived in the least green areas (NDVI <0.37). Additionally, there was evidence that SES-related variables such as ethnicity, education, and neighborhood characteristics modified the relationship between greenness and birth outcomes, with the strongest associations observed in lower SES groups. In analyses stratified by season of birth, the authors observed a negative correlation between NDVI and birth weight in births that occurred during warmer months (April-June). While other studies also found positive associations between greenness and higher birth weights overall [12,13], some studies found either positive associations that were not formally statistically significant [11], more importantly effect estimates moved towards the null with adjustment for covariates [12], and some study results were inconsistent depending on the greenness measure or outcome assessed [10,25]. The birth cohort studies encompassed diverse geographical settings, and effect sizes varied by region. Even though study settings were limited to North America and Europe (Table 1), the observed associations might depend on regional characteristics, including vegetation species type. For example, one study observed a positive association between NDVI and birth weight in Portland, Oregon, but a negative association in Austin, Texas [12].

In addition to birth weight-related outcomes, some researchers investigated the association between greenness and prematurity [10,11,25,35]. Higher odds of preterm birth, defined as being born at fewer than 37 weeks of gestation, was associated with lower exposures to greenness and green spaces around the maternal residence in some studies. Among those born to mothers who lived in cities, those in the upper tertiles of greenness (NDVI >0.43) were less likely (odds ratio (OR) 0.78, 95% CI: 0.61, 0.99) to be born preterm than those in the lowest tertile of greenness[11]. No associations were observed among those living outside cities. Another study based in Lithuania found that mothers who lived more than 1000 m away from the nearest city park had 1.86 (95% CI: 1.18, 2.94) times the odds of delivering their child preterm compared with mothers who lived less than 300 m from the nearest city park [25]. In the large study of births in Texas, associations between greenness and preterm birth were null: those born to mothers who lived in the greenest quartile (NDVI >0.52) during pregnancy were as likely to be born preterm (OR 1.01, 95% CI: 0.99, 1.02) as those born to mothers who lived in the least green quartile (NDVI <0.37) [35]. Similar to findings for birth weight, the variation in results may be due to differences in geography.

One study employed a novel biomarker and assessed telomere length in umbilical cord blood cells collected 24 hours after delivery [20]. Short telomere lengths have been used as a

measure of accelerated aging, and short telomere lengths in cord blood cells has been linked to early insulin resistance as well as impaired fetal growth and brain development in children [41,42]. In this study, a 22% increase in the proportion of green space 5000 m around the maternal residence was associated with on average a 3.62 (95% CI: 0.20, 7.15) % longer telomere.

In combination with the previous literature, the updated research on greenness and birth outcomes contributes evidence for higher levels of greenness resulting in increased birth weight, although studies have not been consistent. Future research should further investigate other birth outcomes beyond birth weight, examine potential effect modification by SES and geographic region, and studies that explore novel biomarkers, such as telomere lengths and other epigenetic marks would be interesting to conduct. Studies should also evaluate the potential mechanisms through which greenness might affect birth outcomes.

Asthma and Allergy

Greenness may affect asthma and allergy-related symptoms by potentially increasing exposure to a greater number and variety of microbes, increasing physical activity, and lowering exposure to air pollution. Conversely, vegetation provides a source of allergens, which may exacerbate allergic responses and may interact with air pollution [43]. Our previous review found inconsistent evidence between greenness and asthma and allergy-related symptoms. One study found that proximity to parks was associated with higher asthma prevalence and another showed that greenness was positively associated with allergic rhinitis, eye, and nose symptoms in an urban setting but observed a negative association in a rural setting [43,44].

Recent studies have remained inconsistent. A study pooling data of seven cohorts from multiple countries found no associations between greenness and allergic rhinitis and aeroallergen sensitization [45]. While greenness was positively associated with allergic rhinitis in Swedish and southern German cohorts, it was negatively associated with this outcome in Dutch and northern German cohorts. There were no associations observed in two Canadian cohorts. Another cohort study of Spanish children similarly found no associations using the full dataset, but detected negative associations with wheezing and bronchitis in some subregions [26]. In a case-control study of only one Eastern European city (Kaunas, Lithuania), an IQR increase in residential NDVI (0.11) was associated with increased odds of being diagnosed with asthma (OR 1.43, 95% CI: 1.10, 1.85).

Although evidence for associations between greenness and asthma or allergy-related symptoms are inconsistent, these results suggest that associations may strongly depend on study area. Future research on this topic may need to identify types of vegetation and other exposures that may differentially influence various allergic outcomes. In addition, prospective studies should also address aspects of seasonality and in different geographic regions.

Cardiovascular Outcomes

Exposure to greenness is thought to affect cardiovascular disease risk by contributing to levels of physical activity, stress, social engagement, noise, and air pollution exposure [46–

48]. Prior research in the field presented evidence of low to intermediate strength for associations between greenness exposure and cardiovascular disease risk [1] The prior literature was dominated by cross-sectional and ecological designs; with one strong prospective study [49]. Recent publications have built onto this literature adding prospective studies.

Three of the studies recently conducted focused on cardiovascular outcomes. An IQR increase in greenness was associated with 3.6 (95% CI: 1.2, 6.0) mmHg lower night time systolic blood pressure recorded with a blood pressure monitors among participants living in the same address their entire life in Belgium [15]. Among participants living at an address different from their birth address at the time of the measurement, only residential greenness exposure in early-life was associated with night systolic blood pressure. This study also adjusted for air pollution and traffic noise and examined both early-life and adult exposure to greenness. In two German birth cohorts, blood lipids that are risk factors for cardiovascular disease (total cholesterol, HDL, LDL and triglyceride) were not found to be associated with greenness exposure in longitudinal analyses [21]. Lastly, in a prospective analysis of individuals in Israel with at least one cardiovascular risk factor, residential greenness was associated with lower odds of myocardial infarction but not stroke, after adjustment for air pollution [50]. Compared to those with NDVI levels from 0–0.1 within 30m around their home, participants with NDVI of 0.1–0.2 had an OR for myocardial infarction of 0.72 (0.33, 0.70). Associations were stronger for those with NDVI levels >0.2; however, give a 95% CI and an effect estimate instead…. This study, based in Southern Israel where much of the terrain is desert, categorized subjects into NDVI exposure categories of 0 to 0.1, 0.1 to 0.2, and above 0.2. This narrow range of exposure levels may limit the generalizability of these results for NVDI as an absolute measure, but may confer some evidence that relative greenness might still be important in certain environments.

Two studies referenced above examined cause-specific mortality, and found that higher levels of NDVI were associated with lower risk of cardiovascular mortality [23,51], but another study [52], did not find an association between NDVI and cardiovascular mortality.

Although the number of studies on greenness and cardiovascular disease is growing, findings are still inconsistent across studies and cardiovascular outcomes suggest that the strength of evidence for greenness and cardiovascular outcomes remains intermediate. More large prospective studies with multiple cardiovascular endpoints would add clarity on the relationship between greenness and cardiovascular disease.

Mortality

Greenness may influence mortality risk by buffering exposure to harmful pollutants, increasing physical activity, providing a setting for social engagement, or through affecting mental health directly, all of which may affect downstream mortality rates. Our previous review found generally consistent evidence that increased greenness is associated with lower mortality based primarily on a small set of prospective analyses.

In the current literature, large prospective studies have been addressing the relationship between greenness exposure, measured through NDVI, and mortality [23,51–53]. A

prospective cohort study analyzed data from 108,630 female nurses in the US followed for 627,008 person-years from 2000–2008 and found that per 0.1 NDVI increase, their mortality was a 12% (95% CI: 6, 18) lower [52]. The strongest findings were for cancer and respiratory mortality, and mediation analyses suggested that the mental health pathway explained 30% of the association. Another large cohort study consisting of 1.3 million adult Canadians across 30 cities showed that higher levels of greenness were associated with lower all-cause mortality, cardiovascular, and respiratory mortality [51]. Associations were strongest among men and those with higher income and education. In a Swiss National Cohort [23], which consisted of 4.2 million adults with 7.8 million follow-up years, researchers found that participants living in areas with higher NDVI had lower levels of mortality from natural causes, respiratory disease, and cardiovascular disease. These associations persisted after adjustment for air pollution and transportation noise. For most mortality outcomes, associations were stronger in urban communities, among younger individuals, and in women, as well as in the highest SES individuals. An ecological study in Spain using 2,148 small administrative areas with an average population of 20,750 people per area found a slight increase in mortality associated with NDVI (risk ratio per IQR (0.265) increase: 1.008; 95% CI: 1.005, 1.011). When stratified only to areas with lower SES, however, NDVI was associated with lower mortality (risk ratio per IQR increase: 0.97; 95% CI: 0.96, 0.98) [53].

Two studies sought to understand whether the relationship between heat and mortality was modified by greenness exposure and found that the association between temperature and mortality was attenuated in greener areas [54,55]. In Portugal, mortality was 14.7% (95% CI: 1.9, 17.5) higher comparing extremely hot days (> 99th percentile of temperature) to other days in areas in the lowest greenness quartile (NDVI <0.23), but only 3.0% (95% CI: 2.0, 4.0) higher in areas in the highest NDVI quartile (>0.48) [55]. In Korea, mortality was 4.1% (95% CI: 2.3, 5.9) higher per 1 Celsius degree increase for days above the 90 percentile of temperature in areas in the lowest NDVI tertile (<0.341) but only 2.2% (−0.5, 5.0) higher in the highest NDVI tertile (>0.542) [54].

In summary, evidence for the relationship between higher levels of greenness and lower mortality strengthened considerably with the addition of large prospective cohort studies corroborating previous findings [23,51,52], although it should be noted that the evidence is not entirely consistent [53]. In addition, a study in Europe and another in Asia showed that greenness may attenuate associations between extreme heat and mortality [54,55]. While new large, prospective cohort studies from different countries added support that for greenness protecting against mortality, further research should investigate potential effect modification by gender, urbanicity, and SES. There is also a need for more studies to understand mediating factors that may explain the relationship between greenness and mortality better. Finally, studies should further pursue the mechanisms that might explain and confirm whether greenness can buffer the effects of extreme heat on mortality.

Other Outcomes

In contrast to our previous review, there were few new studies on chronic disease outcomes such as diabetes, obesity, and cancer. Greenness could possibly be associated with such

chronic outcomes through common mediators of physical activity, harmful environmental exposures, social engagement, or mental health. Below we review the studies examining these chronic outcomes, as well as a few other outcomes that were examined recently.

Related to diabetes, a study of 15-year old adolescents originally enrolled in a German birth cohort found that for each 0.2 increase in NDVI assessed at age 15, insulin resistance was 7.4% (95% CI: 1.1, 13.3) lower [56]. However, associations were attenuated and no longer statistically significant after adjustment for annual mean NO_2 assessed at age 15. A cross-sectional study with highly spatially resolved NDVI data at 0.5 m resolution showed that, among 333,183 adult participants across the United Kingdom, for each higher IQR (0.24) NDVI in a 500m area around participants' homes the BMI was 0.12 (95% CI: 0.10, 0.14) kg/m^2 lower, waist circumference was 0.55 (95% CI: 0.50, 0.61) cm less, and whole body fat mass levels (measured through bio-impedance) were 0.14 (95% CI: 0.10, 0.18) kg lower [9]. Overall, the study found that an IQR increase in NDVI was associated with a 3.2% (95% CI: 2.0, 4.0) lower odds of obesity. It is worth noting that this study measured anthropometry using trained technicians, which likely improves the accuracy of the adiposity measures. Finally, in a case-control study of over 3,800 men living in Montreal, a 0.11 NDVI increase in a 300m buffer around participant's homes was associated with an odds ratio of 0.82 (95% CI: 0.74, 0.92) for prostate cancer [17]. Odds ratios were consistent across multiple buffer sizes, as well as after restricting analyses to controls screened for prostate cancer within the last two years.

There were three additional studies on health outcomes among children. A novel study used an ecological approach in Massachusetts with greenness around schools as the exposure and chronic absenteeism as the outcome, defined as the percent of students missing 10% or more of the total school days in a year [57]. They found that an IQR (0.15) increase in NDVI was associated with 2.6% decrease in chronic school absenteeism. Another study with schoolchildren in Barcelona observed that per IQR (0.08) increase in NDVI there was a 23–34% decreased odds of using spectacles [32]. This could potentially be explained by lower risk of developing myopia among children who are more physically active [58]. Increased green space, especially in forested areas, was also associated with lower prevalence of autism in an ecological study of California school districts using National Land Cover Dataset information [24]. The authors noted, however, that they only observed statistically significant associations in school districts with high road density. Further analyses are required to understand mechanisms that might underlie associations between greenness and autism, which the authors suggested may include buffering traffic-related air pollution and noise, as well as stress reduction in both pregnant mothers and children.

Exposure to nature can potentially act through a multitude of biological pathways to affect health [2,3], and therefore there a number of novel outcomes that might be worth studying. A noteworthy example is a recent ecological study of 100 households in Uganda where investigators examined the relationship between NDVI and malaria metrics such as density of mosquitoes, parasite prevalence, and malaria incidence [59]. These malaria metrics were lower in areas with a lower surrounding NDVI for most urban site, but less so for two rural sites they examined [59]. An intriguing study investigated whether being near urban tree cover during outdoor activities was related to gun assaults [60]. The authors interviewed 135

patients who had been shot with a firearm and 274 community controls in Philadelphia, Pennsylvania from 2008–2011. They geocoded subjects' path points on the day before being assaulted and overlaid these points with tree location data. Compared to cases times (when assaults happened) to control times matched for time of day, having been under a tree cover was inversely associated with gunshot assault (OR 0.70, 95% CI: 0.55, 0.88), especially in low-income areas (OR 0.69, 95% CI: 0.54, 0.87). Although these studies were relatively small in terms of sample size, they demonstrate that greenness may have a range of downstream health effects beyond well-established topics such as physical activity or chronic disease epidemiology.

Conclusions

Based on the recent literature, there is mounting evidence demonstrating associations between greenness and health with more consistent evidence for some outcomes. We found consistent and strong evidence that higher levels of greenness are associated with higher birth weights, higher levels of physical activity, and lower mortality rates. Higher residential greenness was associated with increased birth weights, although this relationship appeared to vary somewhat by geographic region. Findings were less clear for other birth outcomes, including preterm birth. There was consistent evidence of an association between greenness and physical activity, measured with accelerometers as well as through questionnaires. For mortality, consistent evidence across large-scale prospective studies in multiple countries suggests that greenness lowers mortality rates overall. Links between greenness and mental health are growing, with more studies published recently detailing that higher levels of greenness exposure lower levels of depression and depressive symptoms. The evidence on greenness and cardiovascular disease remains less certain, with some positive as well as negative findings. Findings are inconsistent and often contradictory for greenness and asthma and allergies, and more information on vegetation species types may be needed to provide more clarity. Recently, the literature on greenness and health research has broadened to examine a range of health outcomes, including outcomes such as spectacle use in children [32], autism [24], prostate cancer [17], and malaria [59] and gun assaults [60].

Mechanisms through which greenness may promote health remain to be clarified, but the literature suggests that greenness may influence human psychology and provide opportunities for physical activity and social interaction. Although less of a focus of research recently, greenness may also be beneficial by attenuating the detriments from air pollution and noise [61–63]. More studies are needed to identify the mechanisms at play for different greenness and health relationships, perhaps by incorporating potential mediating factors into analyses to assess the proportion of observed associations between greenness and health that might be explained by these factors.

While NDVI data are freely-available and have worldwide spatial coverage, there remains room for improvement in the field of greenness and health. Incorporating datasets with more specific information on vegetation species type, as well as datasets that can distinguish between trees versus grass or other vegetation, would enable researchers to identify specific factors that might drive associations. In addition, spatial layers that incorporate information on the quality and composition of green spaces, perhaps through novel data sources such as

Google Street View [64], would provide the field with a better understanding of exactly what amenities or aspects of nature might influence health. While most studies continue to use the residential address of study participants to estimate exposure to surrounding levels of greenness, some studies have calculated a time-weighted sum based on other important locations, such as schools or commuting environments to reduce exposure misclassification due to participants' movements away from the residential address [8,32]. Other studies strove further to accurately capture surrounding greenness throughout the entire day by using GPS devices to capture participants' real-time locations throughout the day [33]. Tracking study participants' locations throughout the entire day to minimize exposure misclassification is possible with the increased ability to passively collect geographic information from smartphones and other location-tracking personal devices [65]. However, doing so requires appropriate consent and extra privacy considerations and it is uncertain whether estimates of health effects associated greenness exposure would change significantly from estimates that base greenness exposure solely on residential address.s.

Additionally, even with high-resolution information on location, there are still concerns over confounding by health preferences, where individuals who care more about health may be more likely to spend time in greener areas. This potential bias, known as daily selective mobility bias [38], is a potential concern for the field of greenness research. Analyses moving forward should attempt to correct for these factors through incorporating further information about health preferences into study designs, or applying novel analytical approaches [66].

In the literature reviewed, there was evidence showing that SES modifies associations between greenness and birth outcomes [35], diabetes [56], obesity [9], and mortality [9,23,51]. Both individual and area-level SES may alter the ways individuals interact with nature, and more research is required to understand why the influence of greenness on health differs by SES. More research is also needed to explain regional variations. We observed inconsistent associations by region for birth weight [12], allergic rhinitis [45], and asthma and allergy-related symptoms [26,45]. In addition, more research is required outside of North America and Europe, where most studies to date have taken place. Finally, future research initiatives should utilize prospective designs to reduce potential biases and establish temporal relationships between exposure and outcome.

Greenness and health is a research area that can be highly consequential, and may affect multiple health outcomes. Policies and interventions to increase neighborhood levels of greenness are relatively straightforward, potentially low cost, and may have co-benefits for climate mitigation and stormwater runoff control [2]. Yet there are still unanswered questions about how to best incorporate vegetation into communities, what species types are most advantageous for health, what route of exposure is most influential on health, which outcomes are most likely to be influenced by nature, and, fundamentally, whether exposure to nature has a causal effect on health outcomes. Filling the gaps in knowledge in how greenness influences health and health-promoting behaviors will provide researchers, landscape architects, policymakers, and stakeholders with vital information on how to create natural environments that optimize health.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Table 1

Summary of Studies Reviewed

Outcome	Study Designs	Setting	Findings	Strength of Evidence
Physical Activity	3 longitudinal studies[19,30,33] 3 surveys [9,36,37]	2 in Canada, 1 each in USA, Germany, Belgium	There was previously consistent associations between greenness and increased physical activity but few prospective studies. Presently, 3 accelerometry and 2 survey-based studies found positive associations between greenness and physical activity. The odds of using active transportation to commute was higher among those with higher NDVI at the residence, destination, and along the path of the commute.	High
Mental Health	5 cross sectional studies [16,18,22,27,28] 2 longitudinal surveys [29,34] 2 prospective cohort [8,39]	3 in Spain, 1 each in USA, Canada, Korea, United Kingdom, Sweden, 1 combining Spain, Netherlands, Lithuania, and United Kingdom	Previous review found that mental health studies found some evidence of positive associations with self-rated health but was lacking in prospective studies. Current review found associations with lower risk of depression and depression symptoms using some greenness measures but not others. This occurred in some studies of self-rated general health as the outcome. There was limited evidence for a link between greenness and cognitive function. Among children, there was one prospective study showing association with improved cognitive ability.	Intermediate
Birth Outcomes	6 birth cohort studies [10–13,25,35] 1 prospective cohort [20]	5 in USA, 1 each in Belgium, Lithuania	Previously, we found consistent evidence for associations between greenness and higher birth weight. Current review expands on this and found associations with lower risk of preterm birth, low birth weight, and small for gestational age. There may be effect modification by socioeconomic status as well as geographic location.	High
Asthma and Allergy	2 prospective cohorts [26,45] 1 case control [14] 1 ecological study [67]	1 from each of Lithuania, Crete, and Spain, 1 combining data from Sweden, Australia, Canada, and Germany	Prior review did not find consistent evidence for associations between greenness and outcomes related to asthma and allergy. In the present review, we found that pooled data from multiple cohorts resulted in no significant associations between greenness and allergy-related symptoms such as bronchitis, wheezing, asthma, and allergic rhinitis. One study, using data from one city, found a positive association with asthma diagnosis. Overall, there are geographic variations in associations between greenness and asthma and allergy related symptoms. In an ecological study, NDVI predicted number of allergic reaction admissions at hospitals with high accuracy.	Low
Cardiovascular Outcomes	3 prospective cohorts [15,30,50]	1 each in Belgium, Germany, Israel	We previously found ecological and cross sectional studies showing associations with lower cardiovascular disease risk. With the prospective studies in the current review, an association was found between greenness and lower night systolic blood pressure. However, there was no consistent pattern of associations found for blood lipids such as cholesterol, high/low density lipoprotein, and triglycerides.	Low to intermediate

Outcome	Study Designs	Setting	Findings	Strength of Evidence
Mortality	3 prospective cohorts [23,51,52] 3 ecological studies [53–55]	1 in each of USA, Canada, Spain, Portugal, Switzerland, Korea	Previous review included mostly ecological studies and only cohorts of subgroups of the population. The current review found three large, national cohort studies that demonstrated a strong protective effect of greenness on all-cause mortality and mortality from respiratory and cardiovascular diseases. There was some evidence that SES modifies this relationship in two cohort studies and one ecological study. Two ecologic studies show that greenness modifies the relationship between extreme heat and mortality: lower risks of death among areas with higher greenness.	High
Other	Cross sectional study [9,56,68] Case control [17] Case crossover [60] Ecological Study[24,57,59] Longitudinal survey [32]	2 in each of Germany and USA, 1 each in Canada, United Kingdom, Spain, Uganda	Increases in greenness were associated with: lower insulin resistance, lower obesity metrics, lower odds of prostate cancer, lower malaria-related parasites, and higher self-rated general health. Among children and adolescents, greenness was associated with lower rates of spectacle use, school absenteeism, autism, and gun assaults.	N/A

Strength of evidence definitions:

High: evidence is consistent, plausible, and precisely quantified and there is low probability of bias

Intermediate: evidence exists, but not entirely consistent, is not quantified precisely, or may be vulnerable to bias

Low: evidence is inconsistent, implausible, and/or may be vulnerable to bias severely limiting the value of the effect being described