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Growing up green: a systematic review of the influence of greenspace on youth development and health outcomes

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Abstract

Youth growing up in places with more greenspaces have better developmental outcomes. The literature on greenspace and youth development is largely cross-sectional, thus limited in terms of measuring development and establishing causal inference. We conducted a systematic review of prospective, longitudinal studies measuring the association between greenspace exposure and youth development outcomes measured between ages two and eighteen. We searched Cochrane, PubMed, CINAHL, Scopus, and Environment Complete, and included prospective cohort, quasi-experimental, and experimental studies on greenspace and youth development. Study quality was assessed using a 10-item checklist adapted from a previously published review on greenspace and health. Twenty-eight studies met criteria for review and were grouped into five thematic categories based on reported outcomes: cognitive and brain development, mental health and wellbeing, attention and behavior, allergy and respiratory, and obesity and weight. Seventy-nine percent of studies suggest an association between greenspace and improved youth development. Most studies were concentrated in wealthy, Western European countries, limiting generalizability of findings. Key opportunities for future research include: (1) improved uniformity of standards in measuring greenspace, (2) improved measures to account for large latency periods between greenspace exposure and developmental outcomes, and (3) more diverse study settings and populations.

Introduction

Healthy youth development is defined as a "lifelong adaptive process that builds and maintains optimal functional capacity and disease resistance"(1). Aspects of youth development are often divided into the following four dimensions: cognitive, social and

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emotional, speech and language, and fine and gross motor skills(2). Youth health outcomes (such as weight, obesity, and respiratory outcomes) are often metrics used to measure healthy youth development(3, 4). These pediatric health outcomes significantly influence child development as they influence long-term health outcomes throughout the individual's life course (3, 5). Throughout the course of history, interaction with nature has been believed to promote healthy development and improved quality of life among youth(6, 7). Although the impact of the built and natural environment on children and youth is not yet fully understood scientifically, evidence garnered thus far points toward the importance of childhood greenspace exposures(8).

Despite growing evidence suggesting that greenspace exposure promotes healthy youth development, the past five decades have seen stark declines in youths' interaction with nature(6). These declines in youth nature contact have been empirically measured in high income countries, however research suggest that the same phenomenon is occurring in low- and middle-income countries (LMICs)(6, 9). Researchers have attributed these declines to increased overscheduling of youths' time, interaction with technology, fear of stranger danger, and other factors(6). This phenomena has been coined as nature-deficit disorder and is believed to contribute to an array of physical, social, and emotional disorders (6, 10). To investigate the health impacts of nature, many scientists have used greenspace as an exposure to estimate individuals' relationship with nature (11), and over the past decade, a growing body of transdisciplinary research has linked greenspace exposure to a range of positive physical, cognitive, and socioemotional developmental outcomes in children and young people aged 2 to 21 (12–15). These studies suggest that interventions increasing greenspace exposure may constitute a sustainable approach to promoting youth cognitive(16), socio-emotional(17), language (18), and fine and gross motor development (19, 20). Additional studies suggest that greenspace promotes academic achievement for youth aged 8 to 15 (21–23), wellbeing for youth aged 9 to 15(24–26), and other health outcomes (such as cardiovascular health, obesity, and asthma) for children aged 18 years old or younger (27, 28).

While the evidence for greenspace exposure as a positive influence on youth development is promising, other reviews have identified that an overwhelming majority of these studies are cross-sectional (8, 29, 30). Cross-sectional studies are unable to capture the longitudinal nature of youth development and, therefore, inferences drawn from these studies are subject to biases (31–35). Ideally, research on greenspace exposure and youth development should shift from cross-sectional to longitudinal study designs—particularly prospective cohort, quasi-experimental, and experimental studies—in order to understand temporal relationships, latency periods, as well as multiple outcomes. To the best of our knowledge, the findings of published work that fit these study designs have not been consolidated into a single review. Therefore, in this systematic review, we followed PRISMA guidelines (Appendix 1) (36) to evaluate the current state of prospective longitudinal and experimental studies assessing the effect of greenspace exposure on youth development.

Materials and Methods

Search strategy

We used MESH terms to encompass exposure to greenspace from childhood through adolescence, ages 2 through 18 (37). Though there is no universal definition, the Convention on the Rights of the Child states that a child is a human below the age of 18 years (38). While this review sought to examine the impact of greenspace on children and youth, studies with outcomes in children under age 2 were excluded as these years of infancy constitute a sensitive period when exposure to greenspace may produce distinct developmental outcomes requiring separate examination (39). The following combined search string was used to identify relevant studies from Cochrane, Web of Science, PubMed, CINAHL, Scopus, and Environment Complete databases from their earliest available dates through October 9th, 2020: ("green space" OR greenspace OR (green space)) AND (youth OR child* OR adolescent* OR pediatric) AND development. All search results were imported into the systematic review management software Covidence (40).

Screening

Covidence automatically removed duplicate articles found through the search process. Remaining abstracts were independently screened for relevance by two reviewers before passing on to the full text review. Discordant decisions were resolved by a third reviewer. The same double-voting process was followed during the full text review; two reviewers independently voted to include or exclude each study based on predetermined selection criteria. Conflicts during the full text review were discussed and decided on by the entire study team.

Selection criteria

Only studies including longitudinal data or experimental study designs were included. Longitudinal studies were defined as prospective cohort studies that did not measure greenspace exposure and a childhood developmental outcome at the same point in time. Experimental study designs were defined as 1) randomized controlled trials with true randomization or 2) quasi-experimental studies in which a greenspace intervention was tested among study groups without randomization. Studies were required to include prospective measurements of greenspace and developmental outcomes, defined as outcomes measured between ages 2 and 18, inclusive. Studies measuring outcomes related to physical health, cognitive functioning, socioemotional wellbeing, and mental health were included. Studies using the same datasets were included and treated as separate analyses.

Qualitative thematic analysis

Braun and Clarke's six-step method of qualitative analysis was used to generate outcome categories and organize studies into thematic bins, rather than using a pre-determined theoretical framework (41). This inductive approach was chosen to avoid biases and based on our guiding definition of youth development, given there is no current standard for this relatively novel field of research. During the full text screening, each reviewer independently recorded study outcomes. Two reviewers (N.S. and S.S.) conducted a preliminary analysis and generated broad categories to encompass study outcomes, which were discussed, revised, and finalized by the entire team. Once the thematic categories were identified, the authors conducted a brief literature review on the mechanism and pathways for each thematic category. Then, the same two reviewers independently classified all studies into the thematic bins. Four discrepancies in coding were resolved through discussion between all authors(42).

Quantitative quality assessment

Each paper was independently reviewed and scored according to a 10-item quality assessment checklist that was adapted from a previous systematic review of greenspace and health (43). We scored each study based on the following 10 domains derived from the previous systematic review: selection bias, inclusion bias, objectivity of outcome measure, derivation of greenspace measure, measurement of type of greenspace, measurement of use of greenspace, appropriate statistical methodology, effect size reporting, green space variable as main exposure, and level of exposure measurement (individual, ecological, or multi-level) (43). We adapted the quality levels of the initial assessment from a three-tier system (inadequate; adequate; insufficiently described) to a four-tier system (2—good; 1—moderate; 0—poor/unacceptable; N/A—insufficiently described) to align our study with best practices for systematic reviews in the environmental health sciences (43–45). Scores for each quality metric were averaged for studies in the same thematic bins, which were derived from the qualitative thematic analysis described in the prior section. Scores were then visualized in a heat map coded as follows: <1 was "poor or unacceptable" quality, 1 to <2 was "moderate" quality, and 2–3 was "good" quality."

Results

Our literature search identified 1,471 potential studies, from which Covidence removed 755 duplicate articles (Figure 1). Initial abstract screening then eliminated 649 articles deemed irrelevant. Of the remaining 67 studies that underwent full-text screening, 28 were included in the final review (Appendix 2). From this final selection, we found 21 cohort studies (75%), 6 quasi-experimental studies (21.4%), and 1 cross-over experimental study (3.6%) evaluating the impact of greenspace exposure on youth development (Figure 2). All studies were conducted between 2014 and 2020. Figure 3 shows the global distribution of studies across 15 countries. Figure 4 depicts the age ranges captured by each study.

Each study operationalized greenspace exposure in at least one of four ways: (1) the distance to greenspace, (2) type of greenspace (e.g., parks, agriculture, gardens, etc.), (3) use of greenspace (e.g., walking, playing, etc.), and (4) frequency of exposure. Most studies (n = 21, 75%) focused on youths' residential distance to greenspace. These studies spanned multiple greenspace measurement methodologies, the most common being the Normalized Difference Vegetation Index (NDVI), a graphical indicator of live green vegetation. Despite this shared NDVI measure, there were discrepancies in what was coded as greenspace. For example, some studies included agriculture as greenspace, while others did not. Only 7 (25%) studies included type of greenspace (e.g., agriculture, forest, etc.) in their analyses and 8 studies measured frequency and/or usage of greenspace exposure.

Five developmental outcome categories were identified: cognitive and brain development (n = 6, 21.4%), mental health and wellbeing (n = 13, 46.4%), attention and behavior (n = 8, 28.6%), allergy and respiratory (n = 3, 10.7%), and obesity and weight (n = 2, 7.1%). Studies that fit into more than one developmental outcome category were double coded. One study focusing on eyesight development and spectacle use was coded as other, as it did not fit within the selected developmental categories. The results of a brief literature review on commonly proposed mechanisms explaining greenspace exposure's influence on these five developmental categories are presented in Table 1.

The overall quality of the reported studies was moderate, with almost all studies using adequate statistical methodology, adequately reporting effect sizes, and analyzing greenspace as the primary exposure of interest (Appendix 3). The results of the quality assessment by developmental category are visualized in Figure 5. Most studies had moderate risk of selection and inclusion bias, primarily due to small sample sizes or important differences between exposure groups. Outcomes were mostly self-reported across all the studies, introducing potential measurement bias. Greenspace measure derivation was adequately described in most studies, however almost none included details on the type or use of greenspace in their exposure measurement. Lastly, almost all the studies measured greenspace exposure at the ecological level, limiting the interpretation of findings at the individual level.

Cognitive and Brain Development

We identified six studies testing associations between greenspace exposure and youths' cognitive and brain development – four cohort studies(46–49), one quasi-experimental study(50), and one cross-over experiment(51). These studies were published between 2015 and 2019 and were all conducted in high-income European nations (Spain, Germany, the United Kingdom, Austria, Denmark, and the Netherlands). Sample sizes ranged from n = 47 to n = 2,539.

Three studies found a positive association between greenspace exposure and cognitive and brain development (46, 47, 51), while three studies found no association (48–50). Overall, greenspace exposure was positively associated with working memory(46), cognitive performance(51), and white and gray matter volume in several regions of the brain, including regions associated with cognitive performance and working memory (47, 52). One study with 2,593 participants found a positive association between greenspace exposure and cognitive development(46), while another study with 2,429 participants found no such health association(48), suggesting study power did not significantly impact findings. Additionally, the four cohort studies were evenly split between positive health associations(46, 47) and no health associations(48, 52), suggesting study design did not significantly influence findings.

The overall quality of the reported studies in this category was moderate. Several studies showed moderate risk of selection bias (12, 47, 49–51). One study showed moderate risk of inclusion bias (53) and one showed high risk of inclusion bias (46). Studies used a mix of objective and subjective measurements, including validated cognitive performance tests (46, 51), magnetic resonance imaging (47), and participant reports of academic grades (48). Greenspace exposure was well-defined across these studies, with four studies operationalizing greenspace exposure using the NDVI at the individual level (46–49) and two studies using natural features to classify different types of greenspaces (50, 51). Most studies did not, however, measure whether study participants used greenspace, likely biasing findings depending on how often children truly interacted with greenspace. Three cohort studies measured greenspace exposure only at baseline(46, 47), while the fourth cohort study measured greenspace exposure at multiple timepoints throughout the study (48, 49). Most studies controlled for age (46, 47, 50) and SES (46, 48, 49, 52). Notably, controlling for SES in one study attenuated positive health associations, pointing to SES as a potential confounder (49).

Mental Health and Wellbeing

We identified thirteen studies testing associations between greenspace exposure and youths' mental health and wellbeing – eight cohort studies(17, 54–60), four quasi-experimental studies(50, 61–63), and one cross-over experiment(51). These studies were published between 2014 and 2020, with twelve studies conducted in Europe (Denmark, Belgium, Austria, the United Kingdom, and the Netherlands) and one study conducted in the United States (Chicago, Illinois). Sample sizes ranged from 47 to 943,027.

All thirteen studies found positive associations between greenspace exposure and mental health & wellbeing. Overall, greenspace exposure was positively associated with improved prosocial behavior (58), mood (51), emotional resilience (17), and self-determination (63); increased happiness (54) and tonic vagal tone (50); decreased risk of developing schizophrenia (56); and lower incidence of psychiatric disorders, especially among adolescents and urban residents (57). Quasi-experimental studies found within-person improvements in mental health & wellbeing, consistent with findings from previous cross-sectional research (64). Between studies, age was not associated with mental health and wellbeing outcomes.

The overall quality of the reported studies was moderate. Seven studies showed moderate risk of selection bias (50, 51, 54, 57, 62, 63, 65) and one showed high risk due to small sample sizes (61). Three studies showed moderate evidence of inclusion bias (17, 50, 56) and two showed strong evidence (50, 61). These biases were most common in quasi-experimental studies. While most studies included objective measures of health (50, 51, 56–58, 65–67), many also used self-reported measures from study participants and their parents (17, 63, 67), increasing risk of self-reporting bias. Most studies also sufficiently defined their greenspace measure using descriptions of natural features (54, 62), a derivation of the NDVI (n = 4) (55–58), or other satellite imaging or land data (17, 59, 60). However, many did not measure frequency or type of greenspace use. Most studies adjusted for socioeconomic status at the individual level, often through a measure of household income or education(17, 54–60).

Attention and Behavior

We identified eight studies testing associations between greenspace exposure and youths' attention & behavior – five cohort studies (60, 68–71) and three quasi-experimental studies (62, 63, 72). These studies were published between 2017 and 2020, with six conducted in Europe (the United Kingdom, Spain, and Germany), one in Canada, and one in New Zealand. Sample sizes ranged from 100 to 66,283.

Seven studies reported positive associations between greenspace exposure and attention and behavior (60, 62, 63, 68, 69, 71, 72), while one study reported no association (70). Overall, greenspace exposure was associated with short-term prosocial behavior (62); improved self-determination (63), self-regulation (72), and attention (69); lower frequency of peer and conduct problems(60); and decreased odds of an ADHD diagnosis (68, 71). Based on the studies included in this thematic category, age was not significantly associated with attention and behavior outcomes.

The overall quality of these studies was moderate. Risk of self-reporting bias was low, as most outcomes were measured using validated questionnaires (70, 72), computer-based tests (69), ICD codes hospital, and pharmacy records (68, 69). Risk of inclusion bias was also low as most sample sizes were large and representative of source populations. Greenspace exposure was variably defined across these studies. Half used the NDVI (62, 68, 69, 72), while others used the Vegetation Continuous Fields (VCF), an indicator of tree canopy (73), and the Multiple Environmental Deprivation Index (MEDIx), an area-based measure capturing dimensions of health-related environmental drawbacks across the UK (71). Of the five cohort studies, three measured greenspace exposure at baseline, one obtained a ten-year average, and one measured greenspace at multiple time points throughout the study. All but one study (which measured pre- and post-scores) measured attention and behavioral outcomes at multiple timepoints. Only one study measured greenspace usage, and none measured frequency of greenspace use. All analyses were conducted at the individual level, and studies commonly measured greenspace exposure at the individual and ecological levels.

Allergy and Respiratory

We identified three cohort studies testing associations between greenspace exposure and youths' allergy and respiratory development (73–75). This category included studies on asthma, respiratory sinus arrhythmia (RSA), wheezing, allergic rhinitis eczema, and stress reactivity. These studies were published in 2019 and 2020, and were conducted in Europe (Italy, France, Slovenia, Poland, Portugal, and the Netherlands). Sample sizes ranged from 715 to 8063 youths.

All three studies had contradictory findings. One study found that youth living near greenspace had lower prevalence of asthma and rhinitis (74). Another study concluded that exposure to greenspace increased risk of allergic respiratory symptoms (73). The final paper reported no effects of exposure to neighborhood greenness on respiratory outcomes (76). A few possibilities may explain these differing results. First, these three studies were conducted in different countries that may have different proportions of urban, suburban, and rural youth. Additionally, different countries may have different levels of air pollution. An alternative explanation for the inconclusive results is the differences in participants' ages. Participants were measured at ages 4 and 7 in the study that found greenspace to lower the prevalence of asthma and rhinitis in youth (74), ages 3 through 14 in the study that found greenspace exposure to increase risk (73), and ages 11 through 22 in the study that found no significant results(76).

The overall quality of the reported studies was low. One study's findings may be influenced by selection bias since the adolescent subsample (that scored higher on frustration and fearfulness, low scores on effortful control, higher scores on parental psychopathology, and living in a single-parent family) were slightly oversampled, which could have contributed to the null findings (75). Self-reporting bias was also likely present, as all studies predominantly used allergy and respiratory outcomes based on self-reported questionnaires; just one study used objective measures of RSA via stress reactivity, heart rate variability, and standardized residual RSA during speech to predict RSA during rest. Greenspace measures were clearly described and included information on the type of greenspace. Greenspace was operationalized using: the NDVI; the Species Richness Index (SRI) index, an indicator of the total number of species in a community; and as the percentage of neighborhood greenness and land cover exposures. The studies did not, however, include information on greenspace usage or frequency of greenspace use, which may have contributed to the inconclusive findings if children differentially used greenspace. For the three cohort studies included in our review, one study measured greenspace at baseline and two at multiple time points throughout the study. Every study measured outcomes at multiple timepoints. Analyses were conducted at the individual level and meaningful effect sizes with 95% confidence intervals were reported.

Obesity and Weight

We identified two cohort studies testing associations between greenspace exposure and youths' obesity and weight outcomes (77, 78). These studies were published in 2019 and 2020, with one conducted in the Netherlands and the other in the U.S. (Massachusetts). Both studies had large sample sizes (≥400 youths).

One study reported no significant findings after adjusting for confounders (i.e., age, sex, race, parental education/income etc.) (79). Notably, this study failed to collect baseline measurements of the outcome of interest, insulin resistance. The second study reported that shorter distances between youth's homes and greenspace were associated with significantly lower odds of youth overweight status. However, the closer a youth lived to an urban park, the higher the odds of being overweight (78). These contradictory findings may be due to measurement error, effect measure modification clouding a true association, or the absence of an association.

The overall quality of the reported studies was low, with evidence of selection and inclusion bias across studies. Both studies operationalized greenspace exposure using the NDVI at the individual level. One study measured greenspace exposure in addition to air pollution and traffic noise as exposure measurements at the time of outcome measurement (78). Another study measured greenspace exposure at multiple time points prospectively(77). The greenspace exposure measures were well described and included information on type of greenspace with one study using Landsat satellite imagery as a proxy for estimating` NDVI(77). Neither study accounted for greenspace usage or frequency of greenspace exposure, which may have biased findings towards or away from the null. Obesity and weight were measured objectively through body mass index (measured by medical professionals) and insulin resistance (measurement of beta cell function via fasting glucose, insulin, and/or C-peptide concentration).

Other

One cohort study measuring the association between greenspace exposure and spectacles use as a proxy for myopia did not fit into the selected categories. The leading causal theory for this relationship asserts that sunlight exposure is causally linked with reduced spectacles use (80). This study, published in 2017, was conducted in Barcelona, Spain with a sample of 1,812 youth (81). Overall, the study found a 28% reduction in the likelihood of spectacles use per interquartile range increase in time spent in greenspace (81).

The study met all but three quality criteria: inclusion bias, objective outcome measurement, and measurement of type of greenspace. Threat of selection bias was minimal, as the schools selected for this study were socioeconomically representative of Barcelona's school-aged population. Inclusion bias, however, may have been present, as youths included in the longitudinal analysis were more likely to have parents of European ethnicity than of non-European ethnicity, relative to Barcelona's population. This study also exhibited risk of self-reporting bias due to spectacles use being measured through a questionnaire. Greenspace was operationalized using the NDVI and a questionnaire completed by parents determining how frequently youth used greenspaces. Spectacle use was measured twice – once at baseline, and once at the end of the three-year study period. Finally, the study controlled for important confounders, including age, sex, parental education (as a measure of socioeconomic status), preterm birth, and exposure to tobacco smoke during childhood. Effect sizes were reported with 95% confidence intervals.

Discussion

In this systematic review, we evaluated 28 longitudinal studies that assessed the relationship between greenspace and youth development. To our knowledge, this is the first review investigating longitudinal studies of youths' greenspace exposure and youth developmental outcomes. The studies demonstrated mixed results in terms of study quality as well as the direction and magnitude of associations between greenspace exposure and youth developmental outcomes. Our thematic analysis revealed the following categories of greenspace influence on youth development: cognitive and brain development, mental health and wellbeing, attention and behavior, allergy and respiratory, and obesity and weight. We present a summary of our findings for each thematic category in Table 2.

In our review, half of the studies in the Cognitive & Brain Development thematic category found no health association between greenspace and youth development, while the other half found positive health associations. For the studies included in the Cognitive & Brain Development thematic category, there were no specific association between age of exposure and direction (positive, negative, or null) of health associations. The leading mechanistic theory explaining how greenspace exposure impacts cognitive and brain development is the Attention Restoration Theory, which posits that greenspace exposure reduces the burden of mental fatigue and therefore yields positive cognitive and brain development(64, 82). A recently published systematic review supports this theory, suggesting that greenspace exposure has a positive impact on cognitive and brain development(64). One study from our review, conducted in Barcelona, Spain using MRI imaging of the brain, further supports this theory, finding that greenspace exposure was associated with increased white and gray matter volume in clusters of the brain associated with working memory and attention(47).

All studies in the Mental Health & Wellbeing category of this review found positive health associations. Age was not associated with mental health and wellbeing outcomes for the studies included in the Mental Health & Wellbeing thematic category. The primary biological theories explaining how greenspace exposure impacts mental health and wellbeing are the Attention Restoration Theory and Stress Recovery Theory(64, 82). The Stress Recovery Theory posits that humans evolved primarily in natural settings and, therefore, are physiologically and psychologically adapted to natural rather than urban settings(83). Thus, it follows that greenspaces reduce both physiological and psychological stress(83). The Stress Recovery Theory also states that stress reduction through greenspace is both a health benefit and a mechanism through which other health benefits may manifest(84). Many greenspace researchers use both the Attention Restoration Theory and Stress Recovery Theory to complement each other in discussing the health benefits of greenspace(64, 82).

All but one study (which found no health association) in the Attention & Behavior thematic category of this review found positive health associations. There was no evidence that children's age influenced the relationship between greenspace exposure and attention and behavior outcomes. The predominant theory explaining the association between greenspace exposure and children's attention & behavior is the Attention Restoration Theory(85, 86). One landmark study – not included in this review because of its cross-sectional study design – found that youth have better attention and behavior in green settings and that youth with more green play areas have less severe symptoms of attention deficit disorder(85). This study suggested that greenspace access may serve as an alternative or supplement to current pharmaceutical-focused treatments, which often have their own side effects(85).

Most studies in Allergy & Respiratory thematic category found positive health associations, with only one study finding no health association. The current evidence on the association between greenspace exposure and youth allergy and respiratory outcomes is inconclusive(11). Typically, air quality is higher in natural settings and rural areas than in urban settings, resulting in lower prevalence rates of allergies and related respiratory issues in natural and rural areas(11). Thus, it is believed that greenspace may be better for youth allergy prevention and respiratory development. However, the interaction of greenspace and respiratory health is more complex in urban settings(11). Some studies have found that urban greenspace improves air quality and is therefore beneficial for youth respiratory health(87, 88), while other studies have found that exposure to urban greenspace may exacerbate asthma symptoms due to allergens (such as pollen and fungi)(89). For the studies included in this thematic category, younger children (ages 4 to 7) found positive health associations to greenspace, younger to "mid-aged" children (ages 3 to 14) found negative health associations, and older children (aged 11 through 22) found no health association. These age-related differences in the influence of greenspace on Allergy & Respiratory health outcomes is supported by a large literature base suggesting that younger children are more susceptible to environmental health exposures(90–92). Specifically, studies have found that early life environmental exposures significantly increase or decrease the risk of asthma later in adolescence (93, 94). Therefore, it is logical that the studies in this thematic category that included younger children found health associations, whereas the study of older children found no health association. We hypothesize that children in the study that found positive health associations between greenspace and allergy/respiratory outcomes benefited from the improved air quality. In contrast, children in the study that found negative health associations to greenspace may have had higher exposures to allergens.

One of two studies in the Weight & Obesity thematic category found positive health associations between greenspace and youth development, while the other half found no health association. For the studies included in the Weight & Obesity thematic category, there was no evidence that age influenced the relationship between greenspace exposure and this developmental outcome. Current evidence suggests an inverse association between greenspace exposure and being overweight or obese through the following pathways: reduction of negative environmental exposures that promote weight gain, reduction of stress and associated negative health behaviors (e.g., overeating, drinking, and smoking), and promotion of positive health behaviors (e.g., increased physical activity and social cohesion) (95–100). Although the current evidence base suggests that greenspace exposure reduces the risk of obesity, many findings are inconsistent and inconclusive(99–102).

Our review highlights several gaps in knowledge about how greenspace relates to youth development:

- Inconsistent measurements of greenspace exposure and confounders that complicate cross-study comparisons and meta-analyses.
- A dearth of studies conducted in low-income, non-White, and non-Western populations coupled with limited documentation of race and ethnicity.
- Inadequate longitudinal rigor to account for large latency periods between cumulative greenspace exposure and developmental changes in youth.

Thus, we propose the following research agenda for enhancing the evidence base of longitudinal studies on greenspace's influence on youth development:

1. Developing more rigorous and standardized measurements of greenspace

The current evidence base suggests inconsistent, yet promising, research findings on greenspace exposure and youth development(49, 79, 87, 103, 104). As demonstrated by this review's finding, many studies suggest that greenspace promotes healthy youth development. We hypothesize that discrepancies in research findings are partially due to inconsistencies in measurements of greenspace exposure and inconsistent control variables. These discrepancies are major threats to the validity of greenspace research.

Methods to operationalize greenspace exposure are imprecise; discrepancies in type, use, and frequency of exposure create challenges in quantifying dosage of exposure(11, 15, 29). As seen in our review, types of greenspace exposure range from agricultural land to "untouched" nature, to urban tree coverage and more(11, 60, 63, 69, 105). While type of greenspace is commonly, but not always, accounted for in greenspace research, the use and frequency of interaction with greenspace is equally important, but is less often accounted for(11). Only eight studies in this review (29%) incorporated use and/or frequency of greenspace exposure, and many of those studies did not provide clarification on exposure type(51, 62, 63, 72, 81, 106). We would like to highlight one study from this review of 2,727 schoolchildren in Barcelona, Spain that used both questionnaire and GIS data to assess greenspace exposure, thus incorporating distance, use, and frequency of greenspace exposure(81).

Many studies did use NDVI data. The advent of NDVI data means that future studies will have a relatively long historical record of greenspace data to draw on in future studies of youth development. While NDVI is a cheap and accessible metric that would allow for strong historical record, it is important to note that the metric has been criticized for its inaccuracy and oversimplifications of types of greenspaces(107). Other, more accurate and detailed, metrics include the enhanced vegetative index, the moderate resolution imaging spectroradiometer (MODIS) NDVI, the MODIS leaf area index, and light detection and ranging (LiDar)(108).

Air pollution and health outcomes research has begun to overcome similar barriers to research(109). Current air pollution and health research have developed methods to generate person-specific assessments of air pollution exposure; however, there is limited research on the exposure's long-term health outcomes(109). The use of these person-specific exposure assessments can be adapted and applied to greenspace research for more precise measurements of greenspace exposure. However, it is important to consider who would be included in these studies, as the majority of current greenspace and youth development research focuses on white youth from high-income European countries. Greater specificity of greenspace measurement may cause greater selection bias and continue to limit generalizability to other populations. Thus, the tradeoffs between specificity of greenspace measurement and generalizability must be carefully weighed. Nonetheless, future longitudinal studies on greenspace and youth development must account for relevant dimensions of greenspace, namely distance, type, use, and frequency. The inconsistencies in *what* and *how* greenspace is measured and what confounders are controlled for lead to issues establishing causal links between greenspace exposure and youth developmental outcomes.

2. Diversifying sample population

As shown in Figure 3, research on greenspace and youth development has mostly been conducted in high income nations. Most of the studies included in this systematic review come from Europe, with a few originating in the United States, New Zealand, and Canada. With the exception of the United States (which only has 2 studies), all countries have some form of universal healthcare and have low levels of income inequality(110). Furthermore, only 3 of the 28 studies (11%) reported ethnic and racial demographics. Based on the countries in which these studies were conducted, we assume that most studies that did not include racial demographics had primarily White participants. This is a major threat to external validity, as racial minorities have been documented to have poorer access to greenspace, and therefore, less likely to receive the health-promoting effects of greenspace(111–113). Thus, more studies that include non-White populations and report racial and ethnic breakdowns are essential to propel the field forward.

This gap in research is detrimental to greenspace and youth development research as there are complex interactions between SES and access to greenspace. People enjoy living near greenspace and therefore, it has become an expensive luxury(114). Thus, in many countries with inequitable access to greenspace (such as the U.S.) certain communities have less access to greenspace due to historic housing policies and green gentrification (gentrification due to new greening efforts)(111). Additionally, poorly maintained greenspace has been shown in some communities to increase crime and drug violence, and therefore may be feared by the community(115). This complex interaction of social, environmental, and health factors needs to be accounted for in future greenspace and youth development research.

While many of the papers in this study statistically controlled for SES, more rigorous measures are needed to better understand the relationships between SES, greenspace, and youth development. SES is a complex confounder and encompasses both individual/household measures (such as household income, occupation, and education attainment) and more ecological measures (such as neighborhood poverty rate and average household income). Most studies included in this review controlled for a proxy of SES; however, this may be insufficient to understand the complex relationship between SES, greenspace, and youth development(116–119). Ideally, more experimental studies should be conducted to better understand whether, and to what extent, SES interacts with the association between greenspace and youth development.

In addition, no studies from this review were conducted in LMICs. Thus, the current evidence base cannot be generalized to LMICs, where basic needs may be less easily attained. Additionally, different cultures and countries have different views and uses of greenspace and nature contact(120–122). Thus, limiting studies to high-income countries prevents us from understanding the meaning and influence of greenspace in different social fabrics. It is important to note that there are great disparities in access to greenspace in LMICs, where non-white and low-income people live in dense urban centers with limited access to greenspace(123). More research must be conducted in LMICs to better understand how greenspace influences youth development in these settings. Would the youth development benefits be the same in LMICs? Or would other sociocultural factors influence these findings?

3. A push for more longitudinal studies, specifically RCTs

Of the 716 potential studies in this systematic review, only about 4% were longitudinal studies of greenspace and youth development. Of these, just 6 were quasi-experimental studies and 22 were cohort studies. Moreover, many studies failed to collect baseline measurements or measured exposure and outcome at the same time. This lack of methodological rigor may compromise the reliability of longitudinal associations between cumulative greenspace exposure and subsequent changes in developmental outcomes among youth. Our search strategy for this systematic review did not yield any RCTs, despite RCTs being regarded as the gold standard for determining causality(124). Although our search did not yield any RCT that evaluated the effect of greenspace on youth development, RCTs that assess the effects of greenspace on other health outcomes have been published previously(125, 126). For example, one study in Philadelphia, conducted an RCT on 110 vacant lots (greening 37, cleaning up trash in 36, and no intervention in 37) and found that adults living near the greened vacant lots had improved mental health outcomes(125). Similar rigorous research methods could be applied to greenspace exposure and youth development research to establish causal relationships.

Strengths and limitations—To our knowledge, this study is the first to evaluate solely longitudinal and experimental studies of greenspace exposure and youth development outcomes, thus making this systematic review a critical step in establishing causal links between greenspace and youth development. Another strength includes the use of an expert research informationist in determining the six databases used in this study and crafting a search algorithm. Other strengths include unrestricted publication dates for articles, a unique mixed-methods approach to systematic review, and the use of a peer-reviewed 10-item quality assessment for greenspace measures.

However, this study is not without limitations. First, all non-English studies were excluded from this systematic review and, therefore, we may have missed important scientific findings in other languages. The search terms may not have been exhaustive as development encompasses a vast set out of outcomes and greenspace may have been labeled otherwise. Another limitation is that due to the inconsistencies of greenspace exposure measures and differing outcomes, we were unable to conduct a meta-analysis(43). Lastly, this systematic review only focused on peer-reviewed journal articles to ensure quality of papers; important and relevant findings may be available elsewhere.

Conclusion

This systematic review evaluated the current evidence base of prospective, longitudinal and experimental studies on the effects of greenspace exposure on youth developmental outcomes. The 28 studies selected in this review suggest that overall, greenspace may promote positive youth development. More longitudinal studies, specifically RCTs, are warranted to establish this causal relationship. Additionally, future studies should include more rigorous and consistent measures of greenspace exposure and diversification of sample populations.

Acknowledgements

We would like to thank Gloria Willson and John Usseglio from the August C. Long Health Sciences Library at Columbia University Irving Medical Center for their guidance in developing a rigorous search strategy for this review. We would also like thank Dr. Daniel W. Belsky and Dr. Charles C. Branas for their guidance and mentorship in writing this manuscript.

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Data Availability

The data used during the current study are available from the corresponding author on reasonable request.

Appendix 1: PRISMA Report Checklist

#	Item	Guidance	On page #	Author Comments
Title				
1	Title	Identify the report as a systematic review, or systematic review and meta-analysis, as appropriate.	1	**Growing up green: a systematic review of the influence of greenspace on youth development and health outcomes**
Abstract				
2	Structured summary	Provide a structured summary including, as applicable: • Background; • Objectives; • Data sources; • Study eligibility criteria, participants, and interventions; • Study appraisal and synthesis methods; • Results; • Limitations; conclusions and implications of key findings; • Systematic review registration number.	2	Background: Youth growing up in places with more greenspaces have better developmental outcomes. The literature on greenspace and youth development is largely cross-sectional, thus limited in terms of measuring development and establishing causal inference. Objective: We conducted a systematic review of prospective, longitudinal studies measuring the association between greenspace exposure and youth development outcomes measured between ages two and eighteen. Data sources & Study eligibility criteria, participants, and interventions: We searched Cochrane, PubMed, CINAHL, Scopus, and Environment Complete, and included prospective cohort, quasi-experimental, and experimental studies on greenspace and youth development. Study Appraisal and synthesis methods: Study quality was assessed using a 10-item checklist adapted from a previously published review on greenspace and health. Results: Twenty-eight studies met criteria for review and were grouped into five thematic categories based on reported outcomes: cognitive and brain development, mental health and wellbeing, attention and behavior, allergy and respiratory, and obesity and weight. Seventy-nine percent of studies suggest an association between greenspace and improved youth development. Limitations, conclusions, and implications of key findings: Most studies were concentrated in wealthy, Western European countries, limiting generalizability of findings. Key opportunities for future research include: (1) improved uniformity of standards in measuring greenspace, (2) improved measures to account for large latency periods between greenspace exposure and developmental outcomes, and (3) more diverse study settings and populations. Systematic review registration number: N/A
Introduction				
3	Rationale	Describe the rationale for the review in the context of what is already known.	4	Ideally, research on greenspace exposure and youth development should shift from cross-sectional to longitudinal study

#	Item	Guidance	On page #	Author Comments
				designs – particularly prospective cohort, quasi-experimental, and experimental studies, as these studies are better able to establish causality. To the best of our knowledge, the findings of published work that fit these study designs have not been consolidated into a single review. Therefore, in this systematic review, we evaluate the current state of prospective longitudinal and experimental studies assessing the effect of greenspace exposure on youth development.
4	Objectives	Provide an explicit Population-Intervention-Comparator-Outcome-Study Design (PICOS) or Population-Exposure-Comparator-Outcome-Study Design (PECOS) statement as appropriate, detailing the following in relation to the research questions being asked: • Participants • Interventions / Exposures (as appropriate) • Comparisons • Outcomes • Study design	4	Therefore, in this systematic review, we followed PRISMA guidelines (Appendix 1) (36) to evaluate the current state of prospective longitudinal and experimental studies assessing the effect of greenspace exposure on youth development.
Methods				
5	Protocol and registration	Indicate if a review protocol exists, if and where it can be accessed (e.g. web address), and registration information including registration number (if available).	N/A	
6	Eligibility criteria	Specify study characteristics (e.g. PICOS/PECOS, length of exposure) and report characteristics (e.g. years considered, language, publication status) used as criteria for eligibility, giving rationale.	5–6	Only studies including longitudinal data or experimental study designs were included. Longitudinal studies were defined as prospective cohort studies that did not measure greenspace exposure and a childhood developmental outcome at the same point in time. Experimental study designs were defined as 1) randomized controlled trials with true randomization or 2) quasi-experimental studies in which a greenspace intervention was tested among study groups without randomization. Studies were required to include prospective measurements of greenspace and developmental outcomes, defined as outcomes measured between ages 2 and 18, inclusive. Studies measuring outcomes related to physical health, cognitive functioning, socioemotional wellbeing, and mental health were included.
7	Information sources	Describe all information sources (e.g. databases with dates of coverage, contact with study authors to identify additional studies) in the search, and date last searched.	5	The following combined search string was used to identify relevant studies from Cochrane, Web of Science, PubMed, CINAHL, Scopus, and Environment Complete databases from their earliest available dates through October 9th, 2020: (“green space” OR greenspace OR (green space)) AND (youth OR child*

#	Item	Guidance	On page #	Author Comments
				OR adolescent* OR pediatric) AND development.
8	Search	Present full electronic search strategy for at least one database, including any limits used, such that it could be repeated.	5	The following combined search string was used to identify relevant studies from Cochrane, Web of Science, PubMed, CINAHL, Scopus, and Environment Complete databases from their earliest available dates through October 9th, 2020: (“green space” OR greenspace OR (green space)) AND (youth OR child* OR adolescent* OR pediatric) AND development.
9	Study selection	State the process for selecting studies (i.e., screening, eligibility, included in systematic review, and, if applicable, included in the meta-analysis).	5–6	*Screening* Covidence automatically removed duplicate articles found through the search process. Remaining abstracts were independently screened for relevance by two reviewers before passing on to the full text review. Discordant decisions were resolved by a third reviewer. The same double-voting process was followed during the full text review; two reviewers independently voted to include or exclude each study based on predetermined selection criteria. Conflicts during the full text review were discussed and decided on by the entire study team. *Selection criteria* Only studies including longitudinal data or experimental study designs were included. Longitudinal studies were defined as prospective cohort studies that did not measure greenspace exposure and a childhood developmental outcome at the same point in time. Experimental study designs were defined as 1) randomized controlled trials with true randomization or 2) quasi-experimental studies in which a greenspace intervention was tested among study groups without randomization. Studies were required to include prospective measurements of greenspace and developmental outcomes, defined as outcomes measured between ages 2 and 18, inclusive. Studies measuring outcomes related to physical health, cognitive functioning, socioemotional wellbeing, and mental health were included. Studies using the same datasets were included and treated as separate analyses.
10	Data collection process	Describe method of data extraction from reports (e.g., piloted forms, independently, in duplicate) and any processes for obtaining and confirming data from investigators.	6–7	*Qualitative thematic analysis* Braun and Clarke’s six-step method of qualitative analysis was used to generate outcome categories and organize studies into thematic bins, rather than using a pre-determined theoretical framework (44). This inductive approach was chosen to avoid biases and based on our guiding definition of youth development, given there is no current standard for this relatively novel field of research. During the full text screening, each reviewer independently recorded study outcomes. Two reviewers (N.S. and S.S.) conducted a preliminary analysis and generated broad categories to encompass study outcomes, which were discussed, revised, and finalized by the entire team. Once the thematic categories were identified,

#	Item	Guidance	On page #	Author Comments
				the authors conducted a brief literature review on the mechanism and pathways for each thematic category. Then, the same two reviewers independently classified all studies into the thematic bins. Four discrepancies in coding were resolved through discussion between all authors(45). *Quantitative quality assessment* Each paper was independently reviewed and scored according to a 10-item quality assessment checklist that were adapted from a previous systematic review of greenspace and health (41). We scored each study based on the following 10 domains derived from the previous systematic review: selection bias, inclusion bias, objectivity of outcome measure, derivation of greenspace measure, measurement of type of greenspace, measurement of use of greenspace, appropriate statistical methodology, effect size reporting, green space variable as main exposure, and level of exposure measurement (individual, ecological, or multi-level) (41). We adapted the quality levels of the initial assessment from a three-tier system (inadequate; adequate; insufficiently described) to a four-tier system (excellent; medium; poor/unacceptable; insufficiently described) to align our study with best practices for systematic reviews in the environmental health sciences (41–43). Scores for each quality metric were averaged for studies in the same thematic bins, which were derived from the qualitative thematic analysis described in the following section. Scores were then visualized in a heat map coded as follows: lower 10^{th} percentile was “poor” quality, 50^{th} percentile was “moderate” quality, and 90^{th} percentile was “good” quality.
11	Data items	List and define all variables for which data were sought (e.g., PICOS/PECOS, funding sources) and any assumptions and simplifications made.	Appendix 2	Title, author, year, country, study design, sample size, participant age range, race reporting, green space measure, outcome of interest, outcome data source/collection method, other variables included in model, and key findings were extracted from each study.
12	Risk of bias in individual studies	Describe methods used for assessing risk of bias of individual studies (including specification of whether this was done at the study or outcome level), and how this information is to be used in any data synthesis.	6–7	We scored each study based on the following 10 domains derived from the previous systematic review: selection bias, inclusion bias, objectivity of outcome measure, derivation of greenspace measure, measurement of type of greenspace, measurement of use of greenspace, appropriate statistical methodology, effect size reporting, green space variable as main exposure, and level of exposure measurement (individual, ecological, or multi-level).
13	Summary measures	State the principal summary measures (e.g., risk ratio, difference in means).	N/A	Did not conduct a meta-analysis
14	Synthesis of results	Describe the methods of handling data and combining results of studies, if done, including	N/A	Did not conduct a meta-analysis

#	Item	Guidance	On page #	Author Comments
		measures of consistency (e.g., I^2) for each meta-analysis.		
15	Risk of bias across studies	Specify any assessment of risk of bias that may affect the cumulative evidence (e.g., publication bias, selective reporting within studies).	21	• Inconsistent measurements of greenspace exposure and confounders that complicate cross-study comparisons and meta-analyses. • A dearth of studies conducted in low-income, non-White, and non-Western populations coupled with limited documentation of race and ethnicity. • Inadequate longitudinal rigor to account for large latency periods between cumulative greenspace exposure and developmental changes in youth.
16	Additional analyses	Describe methods of additional analyses (e.g., sensitivity or subgroup analyses, meta-regression), if done, indicating which were pre-specified.	N/A	
Results				
17	Study selection	Give numbers of studies screened, assessed for eligibility, and included in the review, with reasons for exclusions at each stage, illustrated with a PRISMA flow diagram.	7	Our literature search identified 1,471 potential studies, from which Covidence automatically removed 755 duplicate articles (Figure 1). Initial abstract screening then eliminated 649 articles deemed irrelevant. Of the remaining 67 studies that underwent full-text screening, 28 were included in the final review (Appendix 2).
18	Study characteristics	For each study, present in a summary table the characteristics for which data were extracted (e.g., study size, PICOS/PECOS, follow-up period) and provide the citations.	Appendix 2	Title, author, year, country, study design, sample size, participant age range, race reporting, green space measure, outcome of interest, outcome data source/collection method, other variables included in model, and key findings were extracted from each study.
19	Risk of bias within studies	Present data on risk of bias of each study and, if available, any outcome level assessment (see item 12).	Appendix 3	Full quality assessment table with risk of bias scores per dimension of quality.
20	Results of individual studies	For all outcomes considered (benefits or harms), present, for each study: (a) simple summary data for each intervention group (b) effect estimates and confidence intervals, ideally with a forest plot (unless such a plot would be misleading)	No forest plot, heat map in Figure 5	
21	Synthesis of results	Present results of each meta-analysis done, including confidence intervals and measures of consistency.	N/A	Did not conduct a meta-analysis.
22	Risk of bias across studies	Present results of any assessment of risk of bias across studies (see Item 15).	Figure 5	The quality assessment across studies by thematic category is presented in a heat map (Figure 5).

#	Item	Guidance	On page #	Author Comments
23	Additional analysis	Give results of additional analyses, if done (e.g., sensitivity or subgroup analyses, meta-regression [see Item 16]).	N/A	
Discussion				
24	Summary of evidence	Summarize the main findings including the strength of evidence for each main outcome; consider their relevance to key groups (e.g., researchers, users, and policy makers).	Table 2	Summary of associations between greenspace exposure and developmental outcomes.
25	Limitations	Discuss limitations at study and outcome level (e.g., risk of bias), and at review-level (e.g., incomplete retrieval of identified research, reporting bias).	8–9 26	The overall quality of the reported studies was fair, with almost all studies using appropriate statistical methodology, adequately reporting effect sizes, and analyzing greenspace as the primary exposure of interest. The results of the quality assessment by developmental category are visualized in Figure 5. Most studies had moderate risk of selection and inclusion bias, primarily because of small sample sizes or important differences between exposure groups. Outcomes were mostly self-reported across all the studies, introducing potential measurement bias. Greenspace measure derivation was adequately described in most studies, however almost none included details on the type or use of greenspace in their exposure measurement. Lastly, almost all the studies measured greenspace exposure at the ecological level, thus limiting the interpretation of findings at the individual level. However, this study is not without limitations. First, all non-English studies were excluded from this systematic review and, therefore, we may have missed important scientific findings in other languages. The search terms may not have been exhaustive as development encompasses a vast set out of outcomes and greenspace may have been labeled otherwise. Another limitation is that due to the inconsistencies of greenspace exposure measures and differing outcomes, we were unable to conduct a meta-analysis(41). Lastly, this systematic review only focused on peer-reviewed journal articles to ensure quality of papers; important and relevant findings may be available elsewhere.
26	Conclusions	Provide a general interpretation of the results in the context of other evidence, and implications for future research.	26	This systematic review evaluated the current evidence base of prospective, longitudinal and experimental studies on the effects of greenspace exposure on youth developmental outcomes. The 28 studies selected in this review suggest that overall, greenspace may promote positive youth development. More longitudinal studies, specifically RCTs, are warranted to establish this causal relationship. Additionally, future studies should include more rigorous and consistent measures of greenspace exposure and diversification of sample populations.
Funding				

#	Item	Guidance	On page #	Author Comments
27	Funding	Describe sources of funding for the systematic review and other support (e.g., supply of data); role of funders for the systematic review.	1	This work was partially funded by NIEHS T32 ES007322.

This PRISMA report was modified by *Environment International* from: Moher D, Liberati A, Tetzlaff J, Altman DG, The PRISMA Group (2009). Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement. PLoS Med 6(7): e1000097. doi:10.1371/journal.pmed1000097. (Changes are minor, with text edits to accommodate the subject matter of the journal and formatting to fit page.)

Appendix 2.: Relevant study characteristics and primary findings from articles evaluating longitudinal association between greenspace exposure and youth development.

Title	Author (year), country	Study design	Sample size (age)	Race and Ethnicity reported	Green space measure	Outcome(s) of interest	Outcome data source/collection method	Other variables included in model
Green Schoolyards in Low-Income Urban Neighborhoods : Natural Spaces for Positive Youth Development Outcomes	Bates et al. (2018), USA	Cohort study	7025 (pre-k - 8th graders)	Y (44.7% African American, 39.2% Latino)	Green schoolyard renovation by the Space to Grow initiative	Social and physical health (a. children's behaviors on the schoolyard and b. changes in student safety, injuries, teasing/ bullying, and gang activity)	a. Child Activity Rating Scale, b. Retrospective self-administered surveys by caregivers and teachers	Race, income, and date of schoolyard renovation

Title	Author (year), country	Study design	Sample size (age)	Race and Ethnicity reported	Green space measure	Outcome(s) of interest	Outcome data source/collection method	Other variables included in model
The associations of air pollution, traffic noise and green space with overweight throughout childhood: The PIAMA birth cohort study.	Bloemsma et al. (2019), Netherlands	Cohort study	3,963 (0–17)	N	Greenness levels surrounding children's homes based on NDVI	Obesity	BMI (weight and height collected by medical professional)	Maternal and parental education, maternal smoking during pregnancy, parental smoking in child's home, and socioeconomic status

Title	Author (year), country	Study design	Sample size (age)	Race and Ethnicity reported	Green space measure	Outcome(s) of interest	Outcome data source/collection method	Other variables included in model
Childhood exposure to green space – A novel risk-decreasing mechanism for schizophrenia?	Cherrie et al. (2019), Denmark	Cohort study	943,027 (10 years and older)	N	Satellite data from the Landsat program at 30 × 30 m resolution	Schizophrenia	Danish Psychiatric Central Research Register using ICD codes	Urbanization, age, sex, and socioeconomic status
A haven of green space: learning from a pilot pre-post evaluation of a school-based social and therapeutic horticulture intervention with children	Chiumento et al. (2018), Denmark	Quasi-experimental study	943,027 (10 years and older)	N	Mean green space and spatial heterogeneity of green space calculated from the NDVI obtained from 30 m resolution remote sensing images from the Landsat archive	Mental health and wellbeing	Schizophrenia and schizophrenia spectrum disorder (admitted to a psychiatric facility, received outpatient care, or visited a psychiatric emergency care unit with a diagnosis of schizophrenia (ICD10: F20 and equivalent ICD-8 codes) and schizophrenia spectrum disorder (ICD10: F20–F29 and equivalent ICD-8 codes).	Birth year, sex, and parents' education, income, and employment status
Green spaces and spectacles use in	Dadvand et al. (2017), Spain	Cohort study	1,812 (7–10 years)	N	Outdoor surrounding greenness at home and	Use of spectacles (proxy for myopia)	Questionnaire	Sex, age, parent ethnicity and indicators of

Title	Author (year), country	Study design	Sample size (age)	Race and Ethnicity reported	Green space measure	Outcome(s) of interest	Outcome data source/collection method	Other variables included in model
schoolchildren in Barcelona.					school and during commuting using NDVI and average annual time spent playing in green spaces based on questionnaires			socioeconomic status (educational achievement and employment status)
The Association between Lifelong Greenspace Exposure and 3-Dimensional Brain Magnetic Resonance Imaging in Barcelona Schoolchildren.	Dadvand et al. (2018), Spain	Cohort study	253 (7–10 years)	N	NDVI derived from RapidEye data, 5×5 resolution.	Regional differences in brain volume	Brain tissue measures/ volumes	Maternal education, Urban Vulnerability Index, sex, age; Inattentiveness, working memory, superior working memory
Lifelong Residential Exposure to Green Space and Attention: A Population-based Prospective Study.	Dadvand, et al. (2017), Spain	Cohort study	1,527 (0–7 years)	N	NDVI and Vegetation Continuous Fields (VCF)	Attention	Conners' Kiddie Continuous Performance Test (K-CPT) at 4–5 years and Network Task (ANT) at 7 years	Age, sex, preterm birth, maternal cognitive performance, maternal smoking during pregnancy, and exposure to environmental tobacco smoke

Title	Author (year), country	Study design	Sample size (age)	Race and Ethnicity reported	Green space measure	Outcome(s) of interest	Outcome data source/collection method	Other variables included in model
Green spaces and cognitive development in primary schoolchildren	Dadvand, P. et al. (2015), Spain	Cohort study	2,593 (7–10 years)	N	NDVI in residence, commute, and school areas, as well as total greenness index (avg. of residential, commute, and school greenness).	Cognitive development (a. Working memory, b. Attention)	a. Computerized n-back test, b. Computerized attentional network test	Age, sex, indicators of socioeconomic status at individual and area levels (maternal education used as indicator of individual-level socioeconomic status, Urban Vulnerability Index used as indicator of area-level socioeconomic status); Traffic-related air pollution measured as a mediator
Association between exposure to the natural environment, rurality, and attention-deficit hyperactivity disorder in children in New Zealand: a linkage study	Donovah et al. (2019), New Zealand	Cohort study	49,923 (0–18 years)	N	NDVI and land-use data from Landcare Research New Zealand	ADHD	Hospital diagnosis or pharmacy records (two or more prescriptions for ADHD drugs)	Sex, ethnicity, mother's educational level, mother's smoking status, mother's age at parturition, birth order, antibiotic use, and low birthweight

Title	Author (year), country	Study design	Sample size (age)	Race and Ethnicity reported	Green space measure	Outcome(s) of interest	Outcome data source/collection method	Other variables included in model
Residential green space in childhood is associated with lower risk of psychiatric disorders from adolescence into adulthood	Engemann et al. (2019), Denmark	Cohort study	943,027 (10 years and older)	N	NDVI calculated using Landsat archive satellite imaging	Psychiatric disorders	Diagnosis upon visit to psychiatric ER, receiving outpatient psychiatric care, or admitted into a psychiatric facility with one of 18 psychiatric disorders	Age (different baselines for each gender), Urbanization, year of birth, gender, parents' education, parents' income, parents' employment status, parents' age, parents' previous psychiatric disorder diagnosis, and residential area socioeconomic status (at the municipal level)

Title	Author (year), country	Study design	Sample size (age)	Race and Ethnicity reported	Green space measure	Outcome(s) of interest	Outcome data source/collection method	Other variables included in model
Association Between Childhood Green Space, Genetic Liability, and the Incidence of Schizophrenia	Engemann et al. (2020), Denmark	Cohort study	19,746 (10 years and older)	N	Mean yearly NDVI within square-shaped zones of 210 m × 210 for each year between birth and the 10th birthday	Schizophrenia	Danish Psychiatric Central Research Register and classified hierarchically as schizophrenia spectrum disorder (ICD-8: 295.x9, 296.89, 297.x9, 298.29–298.99, 299.04, 299.05, 299.09, 301.83; ICD-10: F20–29), affective disorder (ICD-8: 296.x9 [excluding 296.89], 298.09, 298.19, 300.49, 301.19; ICD-10: F30–39)	Parents' socioeconomic status and family history of mental illness
Associations between growing up in natural environments and subsequent psychiatric disorders in Denmark.	Engemann et al. (2020), Denmark	Cohort study	908,553 (10 years and older)	N	NDVI calculated using Landsat archive satellite imaging, then reclassified into urban, agricultural, near natural green space, and blue space.	Psychiatric disorders	Diagnosis upon visit to psychiatric ER, receiving outpatient psychiatric care, or admitted into a psychiatric facility with one of 18 psychiatric disorders	Air pollution, degree of urbanization, year of birth, parents' socioeconomic status (education, income, employment status), parents' history of mental illness, parents' age, and municipal socioeconomic status

Title	Author (year), country	Study design	Sample size (age)	Race and Ethnicity reported	Green space measure	Outcome(s) of interest	Outcome data source/collection method	Other variables included in model
The role of urban neighborhood green space in children's emotional and behavioral resilience	Flouri et al. (2014), England	Cohort study	6,348 (3–7 years)	N	Percentage of space within LSOA that was green based on 2001 Generalized Land Use Database (excluded domestic gardens)	Emotional and behavioral problem	Hyperactivity, emotional symptoms, conduct problems, and peer problems (Strengths and Difficulties Questionnaire (parent-reported))	Sex, ethnicity and age; mother's education and family structure; family socioeconomic disadvantage, life adversity, and neighborhood disadvantage
Early life exposure to green space and insulin resistance: An assessment from infancy to early adolescence.	Jimenez et al. (2020), USA	Cohort study	460 (1–13 yeras)	Y (75% white)	NDVI based on 30 m resolution Landsat satellite imagery	Insulin resistance	Insulin resistance (HOMA-IR)	Age, sex, race/ ethnicity/ parental education/ household income/ neighborhood median household income
Outdoor air pollution, greenspace, and incidence of ADHD: A semi-individual study	Markevych et al. (2018), Germany	Cohortstudy	66,823 (10–14 years)	N	NDVI	ADHD	At least one ICD-10-GM F90 diagnosis by a child/adolescent psychiatrist, neuropediatrician, or psychotherapist	Sex, birth year
Residential and school greenspace and	Markevych et al.	Cohort study	2,429 (10–15 years)	N	Residential and school greenspace	Academic performance	Parent report at age 10 and child	Cohort (GINIplus observation,

Title	Author (year), country	Study design	Sample size (age)	Race and Ethnicity reported	Green space measure	Outcome(s) of interest	Outcome data source/collection method	Other variables included in model
academic performance: Evidence from the GINIplus and LISA longitudinal studies of German adolescents	(2019), Germany				measured by NDVI		self-report at age 15	GINIplus intervention, or LISA cohort), urbanicity, parent education level, single-parent status, income, sex, season during questionnaire response, type of school at age 15, time spent outdoors, time spent on a screen, and general mental health
Neighborhood greenspace and children's trajectories of self-regulation: Findings from the UK Millennium Cohort Study	Mueller et al. (2020), England, Scotland, Wales, and Northern Ireland	Cohort study	13,774 (3–7 years)	N	Multiple Environmental Deprivation Index (MEDIx)	Self-regulation independence and emotional dysregulation	Child Social Behavior Questionnaire	Neighborhood air pollution and deprivation, urbanicity, home physical environment, family background, maternal education and depression, and child-level covariates
Stress Response and Cognitive Performance Modulation in Classroom versus Natural Environments: A Quasi-Experimental Pilot Study with Children	Mygind et al. (2018), Denmark	Quasi-experimental study	47 (10–12 years)	N	Forested area (top of a grassy slope surrounded by trees on three perimeters overlooking a lake)	Stress response and cognitive performance	Heart rate variability (phasic vagal tone) (inter-beat R-R intervals with millisecond accuracy from Polar Team2 Pro chest-strapped HR monitors); Cognitive performance (d2 Test)	Age and gender
Influence of residential land cover on childhood allergic and respiratory symptoms and diseases:	Parmes et al. (2020), Italy, France, Slovenia and Poland	Cohort study	8,063 (3–14 years)	N	Land-cover exposures within a 500 m buffer of each child's residential address using the	Allergic and respiratory symptoms and diseases (wheeze, asthma, allergic	Parental questionnaires	Sex, age, BMI, maternal education, parental smoking, and parental history of allergy

Title	Author (year), country	Study design	Sample size (age)	Race and Ethnicity reported	Green space measure	Outcome(s) of interest	Outcome data source/collection method	Other variables included in model
Evidence from 9 European cohorts					Coordination of Information on the Environment program	rhinitis and eczema)		
Residential neighborhood greenery and children's cognitive development	Reuben et al. (2019), England and Wales	Cohort study	1,658 (5–18 years)	N	NDVI within a 1-mile radius of children's home	Cognitive development (overall cognitive ability at ages a. 5, b. 12, c. 18, and d. Executive function, working memory, and attention ability at age 18)	a. Shortened Wechsler Preschool and Primary Scale of Intelligence-Revised (two subtests used to measure crystallized ability and fluid ability), b. Shortened Wechsler Intelligence Scale for Children - IV (two subtests again to measure crystallized ability an fluid ability), c. Shortened Wechsler Adult Intelligence Scale - IV (two subtests measured crystallized and fluid ability), d. Cambridge Neuropsychological Test Automated Battery	Polygenic score for educational attainment, family socioeconomic status, neighborhood socioeconomic status, and sex
The role of public and private natural space in children's social, emotional and behavioural development in Scotland: A longitudinal study.	Richardson et al. (2017), Scotland	Cohort study	2,909 (4–6 years)	N	Area (%) of total natural space and parks within 500 m of child's home based on Scotland's Greenspace Map (park area, total natural space area, and private garden access)	Social, emotional and behavioral difficulties	Social, emotional, and behavioral difficulty scores (Strengths and Difficulties Questionnaire)	Sex, age, agê2, hours of screen time per day, household highest educational attainment, equivalized annual income and carer's mental component summary score (SF-12 questionnaire)

Title	Author (year), country	Study design	Sample size (age)	Race and Ethnicity reported	Green space measure	Outcome(s) of interest	Outcome data source/collection method	Other variables included in model
The neighbourhood natural environment is associated with asthma in children: A birth cohort study	Rufo et al. (2020), Portugal	Cohort study	1,050 (0–7 years)	N	Residential normalized difference vegetation index (NDVI) and species richness index (SRI)	Allergic diseases and asthma	Self-reported symptoms and history of medical diagnosed questionnaire based on the International Study on Allergy and Asthma Meeting standardized questionnaire completed by participant’s legal guardians at follow-up	Sex, maternal history of asthma, household crowding, and maternal education
Purposeful Outdoor Learning Empowers Children to Deal with School Transitions	Slee et al. (2019), UK	Quasi-experimental study	100 (mean age 11)	N	Nature-based Outdoor Adventure residential program	Mental wellbeing and self-determination	Psychological well-being and self-determination (14-item Warwick-Edinburgh Mental Well-being Scale and 21-item Basic Psychological Needs Satisfaction in Life Scale and semi-structure interviews and informal discussions)	None
Self-regulation gains in kindergarten related to frequency of green schoolyard use	Taylor et al. (2020), Canada	Quasi-experimental study	385 (3–6 years)	N	Portion of the schoolyard that was replaced with softer surfaces (grass, sand, or mulch), planted young trees. Play elements such as a series of stumps for climbing and jumping, a low wooden platform for a stage, tires	Behavioral self-regulation	Child Behavior Rating Scale and The Head-Toes-Knees-Shoulders Task	None

Title	Author (year), country	Study design	Sample size (age)	Race and Ethnicity reported	Green space measure	Outcome(s) of interest	Outcome data source/collection method	Other variables included in model
					and sand embedded into a hillside for climbing, sandboxes, garden boxes, and semicircular seating areas were also installed.			
Residential landscape as a predictor of psychosocial stress in the life course from childhood to adolescence.	Van Aart et al. (2018), Belgium	Cohort study	172 (9–15 years)	Y (all children were white except for one of African origin)	Participant home's proximity to semi-natural, forested, and agricultural areas estimated based on satellite data from the European Coordination of Information on the Environment database	Childhood psychosocial distress (a. happiness, sadness, anger, and anxiousness, b. behavioral problems in the past 6 months, c. stress)	a. Likert scale of 1–10, b. Strengths and Difficulties Questionnaire completed by parents, c. hair cortisol	Distance to nearest major road with traffic counts, noise pollution, air pollution (predictors); Age, sex, socioeconomic status (covariates)
The impact of greening schoolyards on the appreciation, and physical, cognitive and social-emotional well-being of schoolchildren: A prospective intervention study	van Dijk-Wesselius et al. (2018), Netherlands	Quasi-experimental study	2031 (7–11 years)	N	Grassy hills, bushes, tree, tunnels made of tree branches, loose tree branches and garden-like parts	a. Physical activity, b. cognitive wellbeing (attention restoration), c. Social-emotional well-being (prosocial orientation, self-reported social behavior, and emotional functioning)	a. Accelerometers, b. Digit Letter Substitution Test and Sky Search task, c. Social Orientation Choice Card, subscale peer problems and prosocial behavior and Pediatric Quality of life scale	Gender and grade level
Reloading Pupils' Batteries: Impact of Green Spaces on Cognition and Wellbeing	Wallner et al. (2018), Austria	Cross-over experiment study	64 (16–18 years)	N	Inner urban small and heavily used park with a few trees and surrounded by heavily used streets and dense residential areas, a larger park with some tree clumps, or a larger broad	a. Cognitive performance, b. Wellbeing (recuperation, tension/ relaxation, state of mood, readiness for action, readiness for exertion, and alertness)	a. d2-R test (timed test of selective attention), b. self-condition scale by Nitsch	None

Title	Author (year), country	Study design	Sample size (age)	Race and Ethnicity reported	Green space measure	Outcome(s) of interest	Outcome data source/collection method	Other variables included in model
					leaved forest with some scattered meadows and low visitor numbers			
The greener the better? Does neighborhood greenness buffer the effects of stressful life events on externalizing behavior in late adolescence?	Weeland et al. (2019), Netherlands	Cohort study	715 (11–16 years)	N	Percentage of neighborhood greenness	a. Externalizing problems, b. Respiratory sinus arrhythmia, c. Stress reactivity	a. Child Behavior Checklist Stressful life events, b. Heart rate variability in the high-frequency band (0.15–0.40 Hz), c. Standardized residual of RSA during speech (360 s) predicted by RSA during rest (25 min posttest (300 s))	Sex, age at baseline, externalizing behavior at baseline (CBCL), urbanization, and socioeconomic status

For studies that included both cross-sectional and longitudinal analyses, study characteristics from only the longitudinal analyses are depicted in this table.

Appendix 3.: Present data on risk of bias of each study and outcome level assessment

TITLE	AUTHOR (YEAR), LOCATION	POPULATION - SELECTION BIAS (Are the individuals selected to participate in the study likely to be representative of the target population?)	POPULATION – INCLUSION BIAS (Is there evidence of bias in the percentage of selected individuals who provided data for inclusion in the analysis?)	OUTCOME MEASURE (Was the outcome objectively measured or self-reported?)	GREEN SPACE MEASURE – DERIVATION Was derivation of the green space variable well described?)	GREEN SPACE MEASURE – TYPE (Did the green space measure include information on type of green space?)	USE OF GREEN SPACE (Use of green space was measured and included in analysis)	STATI METH (Was a approp statisti metho used?)
Green Schoolyards in Low-Income Urban Neighborhoods: Natural Spaces for Positive Youth Development Outcomes	Bates et al. (2018), **USA**	Moderately representative (1)	Strong evidence of bias (0)	More subjective self-reported (0)	Derivation of green space measure well described (2)	Green space measure included adequate information on type of green space (2)	Measured use of green space adequately (2)	Approp metho
The associations of air pollution, traffic noise and green space with overweight throughout childhood: The PIAMA birth cohort study.	Bloemsma et al. (2019), **Netherlands**	Moderately representative (1)	Moderate evidence of bias (1)	Less subjective self-reported (1)	Derivation of green space measure well described (2)	Green space measure included adequate information on type of green space (2)	Did not measure use of green space (0)	Approp metho
Childhood exposure to green space – A novel risk-decreasing mechanism for schizophrenia?	Cherrie et al. (2019), **Denmark**	Representative (2)	Moderate evidence of bias (1)	Objectively measured outcome (2)	Derivation of green space measure well described (2)	Green space measure did not include information on type of green space (0)	Did not measure use of green space (0)	Approp metho
A haven of green space: learning from a pilot pre-post evaluation of a school-based social and therapeutic horticulture intervention with children	Chiumento et al. (2018), **Denmark**	Not representative (0)	Strong evidence of bias (0)	More subjective self-reported (0)	Derivation of green space measure well described (2)	Green space measure included adequate information on type of green space (2)	Measured use of green space adequately (2)	Moder approp metho
Green spaces and spectacles use in schoolchildren in Barcelona.	Dadvand et al. (2017), **Spain**	Representative (2)	No evidence of bias (2)	Less subjective self-reported (1)	Derivation of green space measure well described (2)	Green space measure included moderate information on type of green space (1)	Measured use of green space adequately (2)	Approp metho
The Association between Lifelong Greenspace	Dadvand et al. (2018), **Spain**	Moderately representative (1)	Moderate evidence of bias (1)	Objectively measured outcome (2)	Derivation of green space measure well described (2)	Green space measure included adequate	Did not measure use of	Approp metho

TITLE	AUTHOR (YEAR), LOCATION	POPULATION - SELECTION BIAS (Are the individuals selected to participate in the study likely to be representative of the target population?)	POPULATION – INCLUSION BIAS (Is there evidence of bias in the percentage of selected individuals who provided data for inclusion in the analysis?)	OUTCOME MEASURE (Was the outcome objectively measured or self-reported?)	GREEN SPACE MEASURE – DERIVATION Was derivation of the green space variable well described?)	GREEN SPACE MEASURE – TYPE (Did the green space measure include information on type of green space?)	USE OF GREEN SPACE (Use of green space was measured and included in analysis)	STATI METH (Was a approp statisti metho used?)
Exposure and 3-Dimensional Brain Magnetic Resonance Imaging in Barcelona Schoolchildren.						information on type of green space (2)	green space (0)	
Lifelong Residential Exposure to Green Space and Attention: A Population-based Prospective Study.	Dadvand, et al. (2017), **Spain**	Moderately representative (1)	No evidence of bias (2)	Objectively measured outcome (2)	Derivation of green space measure well described (2)	Green space measure included adequate information on type of green space (2)	Did not measure use of green space (0)	Approp metho
Green spaces and cognitive development in primary schoolchildren	Dadvand, P. et al. (2015), **Spain**	Moderately representative (1)	Strong evidence of bias (0)	Less subjective self-reported (1)	Derivation of green space measure well described (2)	Green space measure did not include information on type of green space (0)	Did not measure use of green space (0)	Approp metho
Association between exposure to the natural environment, rurality, and attention-deficit hyperactivity disorder in children in New Zealand: a linkage study	Donovah et al. (2019), **New Zealand**	Representative (2)	Moderate evidence of bias (1)	Objectively measured outcome (2)	Derivation of green space measure well described (2)	Green space measure did not include information on type of green space (0)	Did not measure use of green space (0)	Approp metho
Residential green space in childhood is associated with lower risk of psychiatric disorders from adolescence into adulthood	Engemann et al. (2019), **Denmark**	Moderately representative (1)	No evidence of bias (2)	Objectively measured outcome (2)	Derivation of green space measure well described (2)	Green space measure did not include information on type of green space (0)	Did not measure use of green space (0)	Approp metho
Association Between Childhood Green Space, Genetic Liability, and the Incidence of Schizophrenia	Engemann et al. (2020), **Denmark**	Representative (2)	Moderate evidence of bias (1)	Objectively measured outcome (2)	Derivation of green space measure well described (2)	Green space measure did not include information on type of green space (0)	Did not measure use of green space (0)	Approp metho
Associations between growing up in natural	Engemann et al. (2020), **Denmark**	Representative (2)	No evidence of bias (2)	Objectively measured outcome (2)	Derivation of green space measure well described (2)	Green space measure included moderate	Did not measure use of	Approp metho

TITLE	AUTHOR (YEAR), LOCATION	POPULATION - SELECTION BIAS (Are the individuals selected to participate in the study likely to be representative of the target population?)	POPULATION – INCLUSION BIAS (Is there evidence of bias in the percentage of selected individuals who provided data for inclusion in the analysis?)	OUTCOME MEASURE (Was the outcome objectively measured or self-reported?)	GREEN SPACE MEASURE – DERIVATION Was derivation of the green space variable well described?)	GREEN SPACE MEASURE – TYPE (Did the green space measure include information on type of green space?)	USE OF GREEN SPACE (Use of green space was measured and included in analysis)	STATI METH (Was a appro statisti metho used?)
environments and subsequent psychiatric disorders in Denmark.						information on type of green space (1)	green space (0)	
The role of urban neighborhood green space in children's emotional and behavioral resilience	Flouri et al. (2014), **England**	Representative (2)	Moderate evidence of bias (1)	More subjective self-reported (0)	Derivation of green space measure moderately described (1)	Green space measure did not include information on type of green space (0)	Did not measure use of green space (0)	Moder approp metho
Early life exposure to green space and insulin resistance: An assessment from infancy to early adolescence.	Jimenez et al. (2020), **USA**	Moderately representative (1)	Strong evidence of bias (0)	Objectively measured outcome (2)	Derivation of green space measure well described (2)	Green space measure did not include information on type of green space (0)	Did not measure use of green space (0)	Approp metho
Outdoor air pollution, greenspace, and incidence of ADHD: A semi-individual study	Markevych et al. (2018), **Germany**	Representative (2)	No evidence of bias (2)	Objectively measured outcome (2)	Derivation of green space measure well described (2)	Green space measure included adequate information on type of green space (2)	Measured use of green space adequately (2)	Approp metho
Residential and school greenspace and academic performance: Evidence from the GINIplus and LISA longitudinal studies of German adolescents	Markevych et al. (2019), **Germany**	Representative (2)	No evidence of bias (2)	More subjective self-reported (0)	Derivation of green space measure well described (2)	Green space measure included adequate information on type of green space (2)	Measured use of green space adequately (2)	Approp metho
Neighborhood greenspace and children's trajectories of self-regulation: Findings from the UK Millennium Cohort Study	Mueller et al. (2020), **England, Scotland, Wales, and Northern Ireland**	Representative (2)	No evidence of bias (2)	Less subjective self-reported (1)	Derivation of green space measure well described (2)	Green space measure included adequate information on type of green space (2)	Measured use of green space adequately (2)	Approp metho
Stress Response and Cognitive Performance Modulation in Classroom	Mygind et al. (2018), **Denmark**	Moderately representative (1)	Moderate evidence of bias (1)	Objectively measured outcome (2)	Derivation of green space measure moderately described (1)	Green space measure included moderate information	Measured use of green space	Approp metho

TITLE	AUTHOR (YEAR), LOCATION	POPULATION - SELECTION BIAS (Are the individuals selected to participate in the study likely to be representative of the target population?)	POPULATION – INCLUSION BIAS (Is there evidence of bias in the percentage of selected individuals who provided data for inclusion in the analysis?)	OUTCOME MEASURE (Was the outcome objectively measured or self-reported?)	GREEN SPACE MEASURE – DERIVATION Was derivation of the green space variable well described?)	GREEN SPACE MEASURE – TYPE (Did the green space measure include information on type of green space?)	USE OF GREEN SPACE (Use of green space was measured and included in analysis)	STATI METH (Was a appro statisti metho used?)
versus Natural Environments: A Quasi-Experimental Pilot Study with Children						on type of green space (1)	moderately (1)	
Influence of residential land cover on childhood allergic and respiratory symptoms and diseases: Evidence from 9 European cohorts	Parmes et al. (2020), **Italy, France, Slovenia and Poland**	Representative (2)	No evidence of bias (2)	Less subjective self-reported (1)	Derivation of green space measure well described (2)	Green space measure included adequate information on type of green space (2)	Measured use of green space adequately (2)	Appro metho
Residential neighborhood greenery and children's cognitive development	Reuben et al. (2019), **England and Wales**	Moderately representative (1)	No evidence of bias (2)	Objectively measured outcome (2)	Derivation of green space measure well described (2)	Green space measure included adequate information on type of green space (2)	Measured use of green space adequately (2)	Appro metho
The role of public and private natural space in children's social, emotional and behavioural development in Scotland: A longitudinal study.	Richardson et al. (2017), **Scotland**	Representative (2)	No evidence of bias (2)	Less subjective self-reported (1)	Derivation of green space measure well described (2)	Green space measure included adequate information on type of green space (2)	Measured use of green space adequately (2)	Appro metho
The neighbourhood natural environment is associated with asthma in children: A birth cohort study	Rufo et al. (2020), **Portugal**	Representative (2)	Strong evidence of bias (0)	More subjective self-reported (0)	Derivation of green space measure well described (2)	Green space measure did not include information on type of green space (0)	Did not measure use of green space (0)	Appro metho
Purposeful Outdoor Learning Empowers Children to Deal with School Transitions	Slee et al. (2019), **UK**	Moderately representative (1)	No evidence of bias (2)	More subjective self-reported (0)	Derivation of green space measure poorly described (0)	Green space measure did not include information on type of green space (0)	Measured use of green space adequately (2)	Appro metho

TITLE	AUTHOR (YEAR), LOCATION	POPULATION - SELECTION BIAS (Are the individuals selected to participate in the study likely to be representative of the target population?)	POPULATION – INCLUSION BIAS (Is there evidence of bias in the percentage of selected individuals who provided data for inclusion in the analysis?)	OUTCOME MEASURE (Was the outcome objectively measured or self-reported?)	GREEN SPACE MEASURE – DERIVATION Was derivation of the green space variable well described?)	GREEN SPACE MEASURE – TYPE (Did the green space measure include information on type of green space?)	USE OF GREEN SPACE (Use of green space was measured and included in analysis)	STATI METH (Was a approp statisti metho used?)
Self-regulation gains in kindergarten related to frequency of green schoolyard use	Taylor et al. (2020), **Canada**	Moderately representative (1)	Moderate evidence of bias (1)	Objectively measured outcome (2)	Derivation of green space measure well described (2)	Green space measure did not include information on type of green space (0)	Measured use of green space adequately (2)	Approp metho
Residential landscape as a predictor of psychosocial stress in the life course from childhood to adolescence.	Van Aart et al. (2018), **Belgium**	Moderately representative (1)	No evidence of bias (2)	Less subjective self-reported (1)	Derivation of green space measure well described (2)	Green space measure included adequate information on type of green space (2)	Did not measure use of green space (0)	Approp metho
The impact of greening schoolyards on the appreciation, and physical, cognitive and social-emotional well-being of schoolchildren: A prospective intervention study	van Dijk-Wesselius et al. (2018), **Netherlands**	Moderately representative (1)	No evidence of bias (2)	Less subjective self-reported (1)	Derivation of green space measure well described (2)	Green space measure included adequate information on type of green space (2)	Measured use of green space moderately (1)	Approp metho
Reloading Pupils' Batteries: Impact of Green Spaces on Cognition and Wellbeing	Wallner et al. (2018), **Austria**	Moderately representative (1)	No evidence of bias (2)	Less subjective self-reported (1)	Derivation of green space measure well described (2)	Green space measure included adequate information on type of green space (2)	Measured use of green space adequately (2)	Approp metho
The greener the better? Does neighborhood greenness buffer the effects of stressful life events on externalizing behavior in late adolescence?	Weeland et al. (2019), **Netherlands**	Moderately representative (1)	Moderate evidence of bias (1)	Objectively measured outcome (2)	Derivation of green space measure moderately described (1)	Green space measure included moderate information on type of green space (1)	Did not measure use of green space (0)	Approp metho

Abbreviations:

NDVI	Normalized Difference Vegetation Index
RSA	respiratory sinus arrythmia

SES	socioeconomic status
LMIC	low- and middle-income countries

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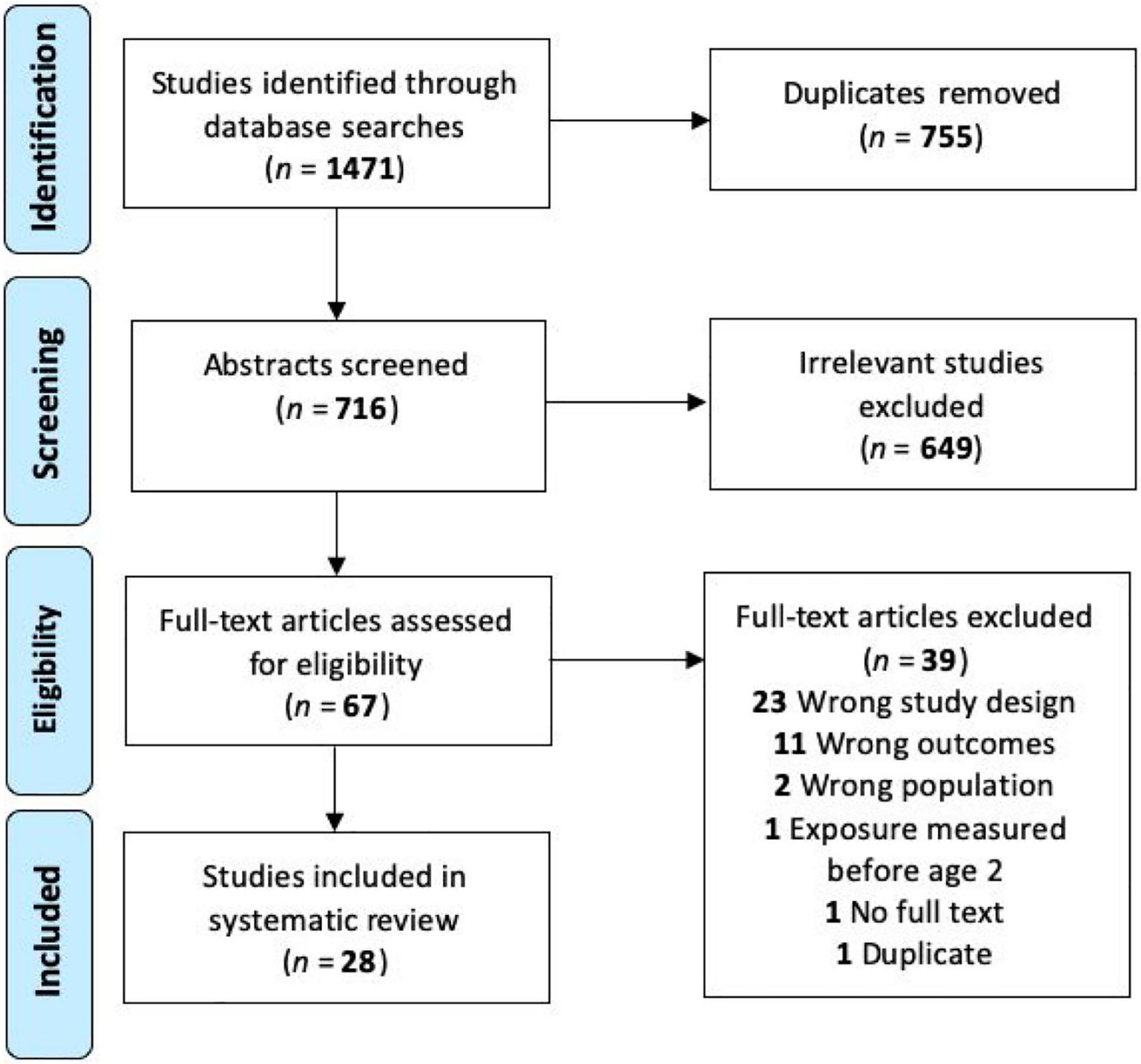


Figure 1.
Flow diagram of literature search, screening, and full-text review results.

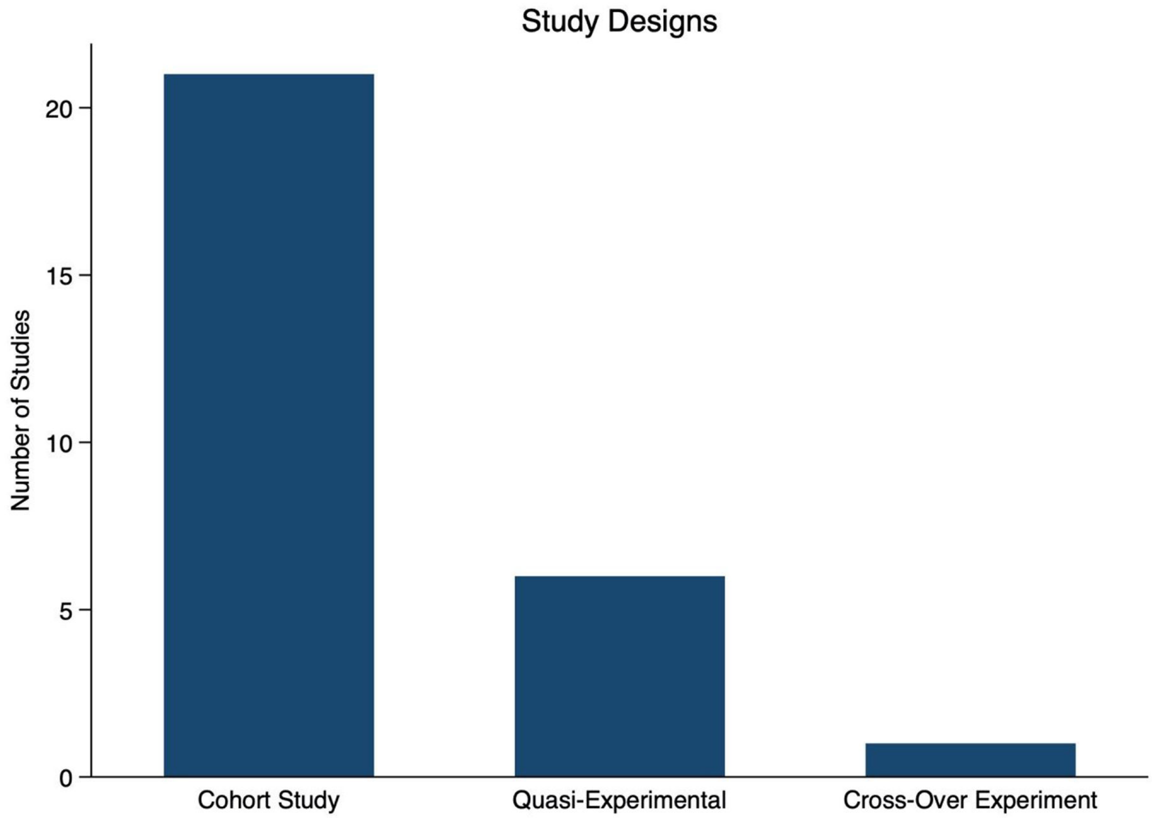


Figure 2.

Study design distribution in this systematic review.

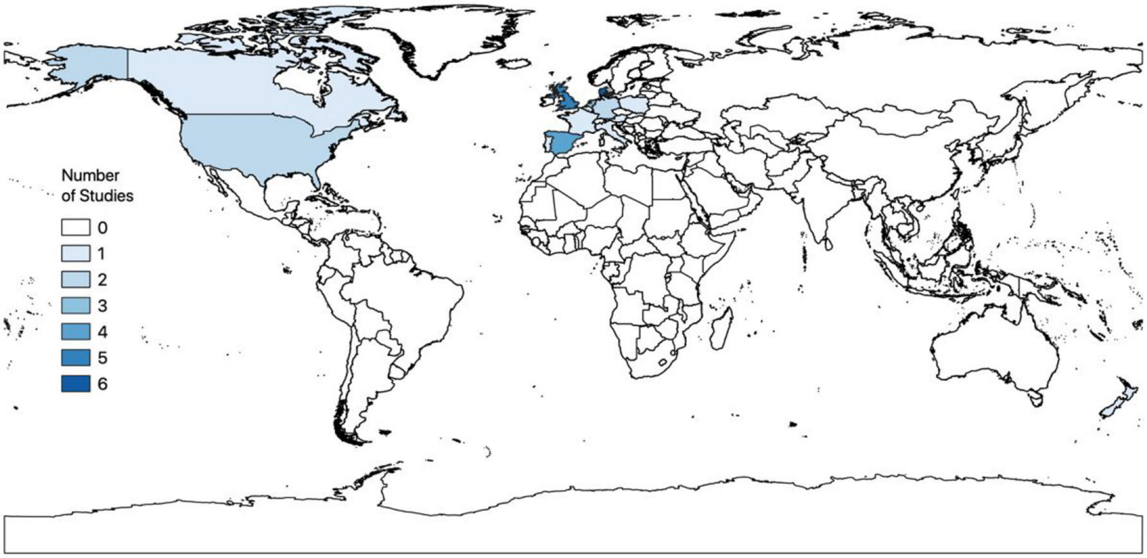


Figure 3.

Global distribution of longitudinal and experimental studies examining greenspace and youth development by country.

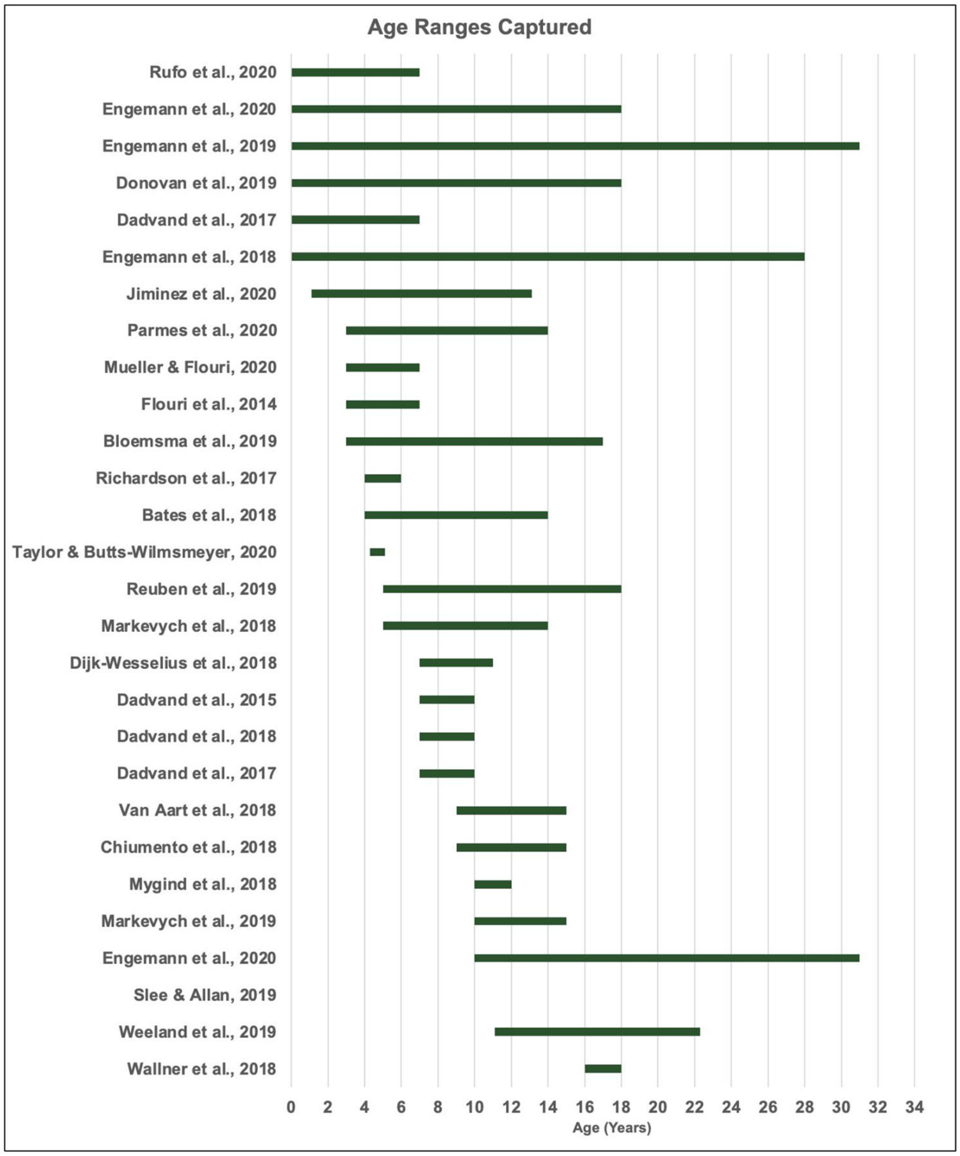


Figure 4.

Age ranges captured by each study.

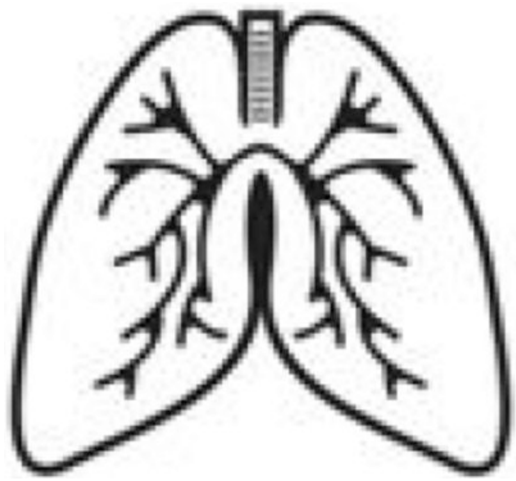
Figure 5.

Heat map of quality scores across developmental thematic categories. Scores were categorized as follows: 0= poor/unacceptable quality, 1= medium quality, 2 = excellent quality.

Table 1.

Commonly proposed mechanisms linking greenspace exposure to youth development by health outcome categories.

Cognitive and Brain	
	Greenspace is thought to support cognitive integrity and healthy brain development because it engages the mind effortlessly, without demanding focused attention, and aids in recovery from ‘attention fatigue’, according to Attention Restoration Theory.
Mental Health and Wellbeing	
	Greenspace is thought to benefit mental health and enhance wellbeing through a variety of mechanisms: Natural settings are less mentally taxing and restorative, according to Attention Restoration Theory (see above); Humans are evolutionarily better adapted to natural rather than urban settings, according to Stress Recovery Theory; Greenspace is associated with healthier environmental conditions, such as lower temperatures, less air pollution and noise; Greenspace promotes physical activity; Greenspace increases and enhances social interactions.
Attention and Behavior	

<table>
<tr><td></td><td>Greenspace is thought to promote self-regulation and concentration among youth as it induces restful cognitive engagement, rather than focused attention, as proposed by the Attention Restoration Theory (see above).</td></tr>
<tr><td colspan="2">Allergy and Respiratory</td></tr>
<tr><td></td><td>Greenspace is thought to influence respiratory health by improving air quality, supporting allergy prevention and respiratory development. However, exposure to urban greenspace may exacerbate asthma symptoms due to the proliferation of allergens.</td></tr>
<tr><td colspan="2">Obesity and Weight</td></tr>
</table>

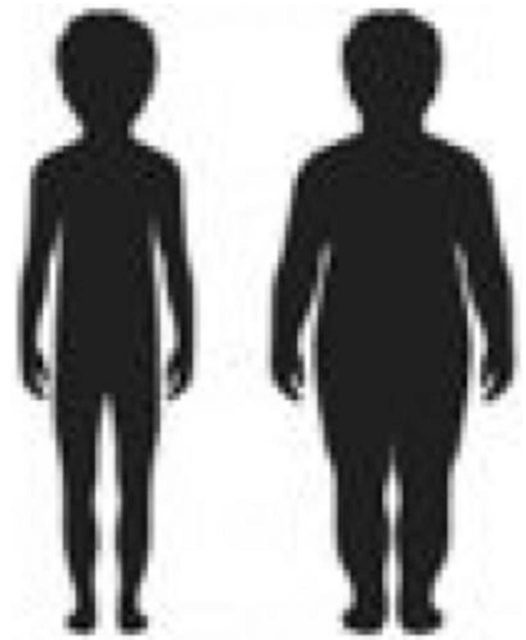
	Greenspace is thought to prevent overweight and obesity in children by reducing negative environmental exposures that promote weight gain, stress and associated negative health behaviors (e.g., overeating, drinking and smoking), and promoting positive health behaviors (e.g., increased physical activity and social cohesion).

Table 2:

Summary of associations between greenspace exposure and developmental outcomes.

Developmental Outcome	Direction of Health Impact	Greenspace exposure was associated with…
Cognitive and Brain Development **(n=6 studies)**	Positive (n=3) No Association (n=3)	• Improved working memory. • Increased cognitive performance. • Increased white and gray matter volume in different regions of the brain, including regions associated with cognitive performance and working memory.
Mental Health and Wellbeing **(n=13)**	Positive (n=13)	• Improved pro-social behavior. • Improved mood • Improved tonic vagal tone. • Increased emotional resilience. • Increased self-determination. • Increased happiness. • Decreased risk of developing schizophrenia. • Decreased incidence of developing psychiatric disorders, especially among adolescents and urban residents.
Attention and Behavior **(n=8)**	Positive (n=7) No Association (n=1)	• Increased short-term pro-social behavior. • Improved self-determination. • Improved self-regulation. • Improved attention. • Lower frequency of peer and conduct problems. • Lower odds of an ADHD diagnosis.
Allergy and Respiratory **(n=3)**	Positive (n=1) Negative (n=1) No Association (n=1)	• Increased risk of allergic respiratory symptoms. • Lower prevalence of asthma and rhinitis.
Obesity and Weight **(n=2)**	No Association (n=1) Conflicting (n=1)	• Lower odds of being overweight. • Higher odds of being overweight in urban settings.
Other **(n=1)**	Positive (n=1)	• Decreased risk of spectacles use.