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Review

Greenspace exposure and children behavior: A systematic review

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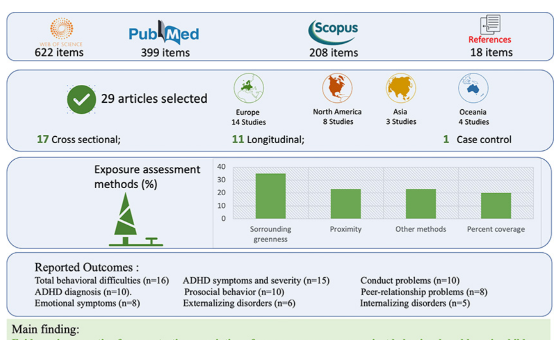
HIGHLIGHTS

- Evidence on the association of greenspace exposure with child behavior is accumulating.
- We found indications for a beneficial impact of greenspace exposure on child behavior.
- Total behavioral difficulties and ADHD showed consistent associations with greenspace.

GRAPHICAL ABSTRACT



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ABSTRACT

We systematically reviewed the existing evidence (until end of November 2021) on the association between long-term exposure to greenspace and behavioral problems in children according to the PRISMA 2020. The review finally reached 29 relevant studies of which, 17 were cross-sectional, 11 were cohort, and one was a case-control. Most of the studies were conducted in Europe ($n = 14$), followed by the USA ($n = 8$), and mainly ($n = 21$) from 2015 onwards. The overall quality of the studies in terms of risk of bias was "fair" (mean quality score = 5.4 out of 9) according to the Newcastle–Ottawa Scale. Thirteen studies (45%) had good or very good quality in terms of risk of bias. The strength and difficulty questionnaire was the most common outcome assessment instrument. Exposure to the greenspace in the reviewed studies was characterized based on different indices (availability, accessibility, and quality), mostly at residential address locations. Association of exposure to different types of greenspace were reported for nine different behavioral outcomes including total behavioral difficulties ($n = 16$), attention deficit hyperactivity disorder (ADHD) symptoms and severity ($n = 15$), ADHD diagnosis ($n = 10$), conduct problems ($n = 10$), prosocial behavior ($n = 10$), emotional symptoms ($n = 8$), peer-relationship problems ($n = 8$), externalizing disorders ($n = 6$), and internalizing disorders ($n = 5$). Most

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of the reported associations (except for conduct problems) were suggestive of beneficial association of greenspace exposure with children's behaviors; however, the studies were heterogeneous in terms of their exposure indicators, study design, and the outcome definition.

Contents

1. Introduction

The ongoing urbanization has led to an increase in the number of children being born and raised in urban areas (Nations, 2014). Urban living is often associated with a stressful and sedentary lifestyle, increased exposure to urban-related environmental hazards such as air pollution, noise, and heat, and limited access or exposure to natural environments (Vlahov and Galea, 2002; Gregg et al., 2003). Natural environments, including greenspace (has been defined by the U.S. Environmental Protection Agency as "*land that is partly or completely covered with grass, trees, shrubs, or other vegetation*" (US, 2021)), have been suggested to improve mental and physical health and wellbeing (Barton and Rogerson, 2017; Roberts et al., 2019). Exposure to greenspace has been suggested to be associated with improved overall mental and physical health of children, including behavioral outcomes (McCormick, 2017; Nicole, 2018; Parmes et al., 2020). The ability of greenspace to exert such benefits has been suggested to be through socio-behavioral and environmental pathways (Markevych et al., 2017). Socio-behavioral pathways encompass an increase in physical activity, social cohesion, and attention restoration and a decrease in stress (Markevych et al., 2017). Additionally, greenspace could exert its benefits through environmental pathways, including mitigating the exposure to urban-related environmental hazards such as air pollution, noise, and heat and enriching microbiota diversity (Selway et al., 2020; Nieuwenhuijsen, 2021). As a result, an increasing number of studies have evaluated the association of greenspace exposure with neurodevelopment, including behavioral outcomes in children (McCormick, 2017).

Behavioral problems are common in children. For example, it has been estimated that one out of seven children aged two to eight years in the United States suffers from different types of behavioral, mental, or developmental problems (Data and Statistics on Children's Mental Health[cited, 2021). Evidence that children spend less time in nature than previous generations (Clements, 2004) has prompted researchers to explore the connection between exposure to greenspace and the global rise in the prevalence of mental and behavioral problems (Putra et al., 2020). Previous studies assessing this association were mainly of experimental design looking at the "therapeutic effects" of short-term contact with greenspace on neurodevelopmental impairments such as attention deficit-hyperactivity disorders (ADHD) in children who were affected by these conditions (Faber Taylor and Kuo, 2011; Taylor et al., 2001). More recently, a growing number of epidemiological studies have investigated the association of long-term exposure to greenspace with neurodevelopment, including behavioral development, in children from the general population (McCormick, 2017; Putra et al., 2020). Higher levels of surrounding greenspace have been reported to be associated with better behavioral development (Liao et al., 2020). Inverse associations have been reported between higher residential greenspace and ADHD symptoms and incidence (Amoly et al., 2014; Balseviciene et al., 2014). Increasing exposure to nature through adding greenspace to schoolyards promoted the social behaviors of children (Raney et al., 2019). A major part of the evidence on greenspace and children mental health suggests a beneficial role of greenspace exposure on children's behavioral difficulties (Vanaken and Danckaerts, 2018). However, some other studies did not find such association between neighborhood greenspace and outcomes such as self-regulation in children (Mueller and Flouri, 2020).

In general, the evidence on the association between exposure to greenspace and children's behavior is increasing rapidly and in some cases is equivocal. Inconsistencies might arise from how green space exposure is measured, outcome assessment, and other methodological issues such as study design and statistical methods (Putra et al., 2021). We aimed to systematically review the existing evidence on the association between long-term exposure to greenspace and behavioral problems in children. We also aimed to explore the methodological issues in the studies in terms of exposure and outcome assessment to better understand the sources of heterogeneities, to propose further research insights.

2. Methods

The review was conducted according to the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) statement (Page, 2021). We developed a systematic review protocol before the initiation of the review, and all the review team members adhered to the protocol that was set at the beginning of the review.

2.1. Inclusion and exclusion criteria

We included original articles written in English and reporting on observational studies with quantified estimates of the association between long-term exposure to greenspace and at least one of the behavioral outcomes in the general population until the age of 18 years (the age group in this study was all children as defined those up to 18 years old) (Table S1). Studies were excluded if the exposure variable was not quantified (e.g. binary variables such as presence or absence of a park without further information about the distance or satisfaction with neighborhood greenspace [yes/no] without a rating on a scale), or the study population only consisted of patients or non-healthy populations (e.g. children with autism at baseline). We also excluded review articles, semi- or natural experimental studies, and qualitative studies.

2.2. Information sources

We searched three databases to find relevant articles: PubMed (National Library of Medicine), Scopus, and Web of Science (including WOS, KJD, RSCI, SCIELO). The searches were conducted on November 29, 2021. The content of search strategy used for PubMed, Scopus, and Web of Science databases are provided in Supplementary tables S2–S4 respectively. In addition to the databases search, we also conducted a manual search of the references lists of the retrieved original studies or review articles (Putra et al., 2020; Vanaken and Danckaerts, 2018; Islam et al., 2020) to identify additional studies. The identified studies in reference checking step underwent abstract and full-text evaluation for the assessment of the eligibility of inclusion in the review. The overview chart of the search strategy is presented in Fig. 1.

2.3. Search strategy

To build a more comprehensive search queries, and to gain a broader view on the keywords in the context, and capture articles within the scope of the review, at first we searched relevant systematic reviews on the greenspace and natural environment (as the exposure of interest), and different childhood behavioral problems (as the outcome of interest) (Putra et al., 2020; Vanaken and Danckaerts, 2018; Islam et al., 2020). We then made the search queries based on the PECO (Population, Exposure, Comparison, and Outcome) framework (Morgan et al., 2018), by combining the keywords on the exposure (e.g. green space(s), greenness, normalized difference vegetation index (NDVI)); outcome (e.g. neurodevelopment(al), motor development, behavio(*u*)ral problems, hyperactivity, Attention Deficit Hyperactivity Disorder (ADHD), Strengths and Difficulties Questionnaire (SDQ)); and the study population (e.g. child, children, adolescent(s), adolescence, teenager(s), teen, childhood, early life, prenatal, and postnatal) (Table S1).

2.4. Study selection

The study selection process was conducted in the Rayyan online platform (Ouzzani et al., 2016). After duplicate removal, the title and abstract of the articles were screened to exclude the articles that did not meet the review criteria. Afterwards, the full texts of the remaining articles were examined by two teams of reviewers (CK, MB, PK, and LMB) independently to decide which articles met the inclusion criteria and were to be included in the review. In the case of disagreements, another reviewer (PD) checked the paper for inclusion or exclusion in the review.

2.5. Data extraction and data items

After completion of the selection process, relevant data on study characteristics (design, location, time of the study), study population (number, age, and sex of participants), exposures (type of exposure, source of exposure data, exposure assessment method, exposure allocation method), outcomes (the type of outcome, method of outcome measurements, outcome data sources), statistical methods (statistical models, level of adjustments, covariates used in the models), and results (main finding, effect sizes) were extracted. We checked the study names (if available) and population in the selected papers to avoid the overlap of the study population in the papers.

2.6. Study risk of bias assessment

The risk of bias (ROB) of the included studies was assessed by the Newcastle–Ottawa Scale (NOS), as recommended in the Cochrane Handbook for Systematic Reviews of Interventions (Higgins et al., 2019). The NOS includes three domains: (i) selection (four items), (ii) comparability (one item), and (iii) ascertainment of exposure/outcome (three items) (Wells et al., 2000). For cohorts and case-control studies, all items except the comparability can earn one scoring star (the comparability item can earn a maximum of two stars). The sum of the earned stars (maximum of nine) is the ROB score of each study. As NOS has not originally been developed for environmental epidemiology studies, we slightly modified the NOS items (especially for the exposure ascertainment domain) to be applicable in the field of environmental epidemiology (Sakhvidi et al., 2020). For greenspace exposure assessment we used "the location of exposure allocation" as a selected aspect for quality assessment and considered exposure assessment via geocoding at the residential location as the highest exposure assessment quality. Table S5 presents the detailed description of each item in the risk ROB assessment of each study design. For cross-sectional studies, we used a modified version of the NOS for cohort studies (Sakhvidi et al., 2020). Different cut-offs have been reported to categorize the studies based on the NOS score. While the definition of cut-offs is not stated in the original NOS guideline, we defined five categories of risk of bias according to the NOS score which also is reported in other studies

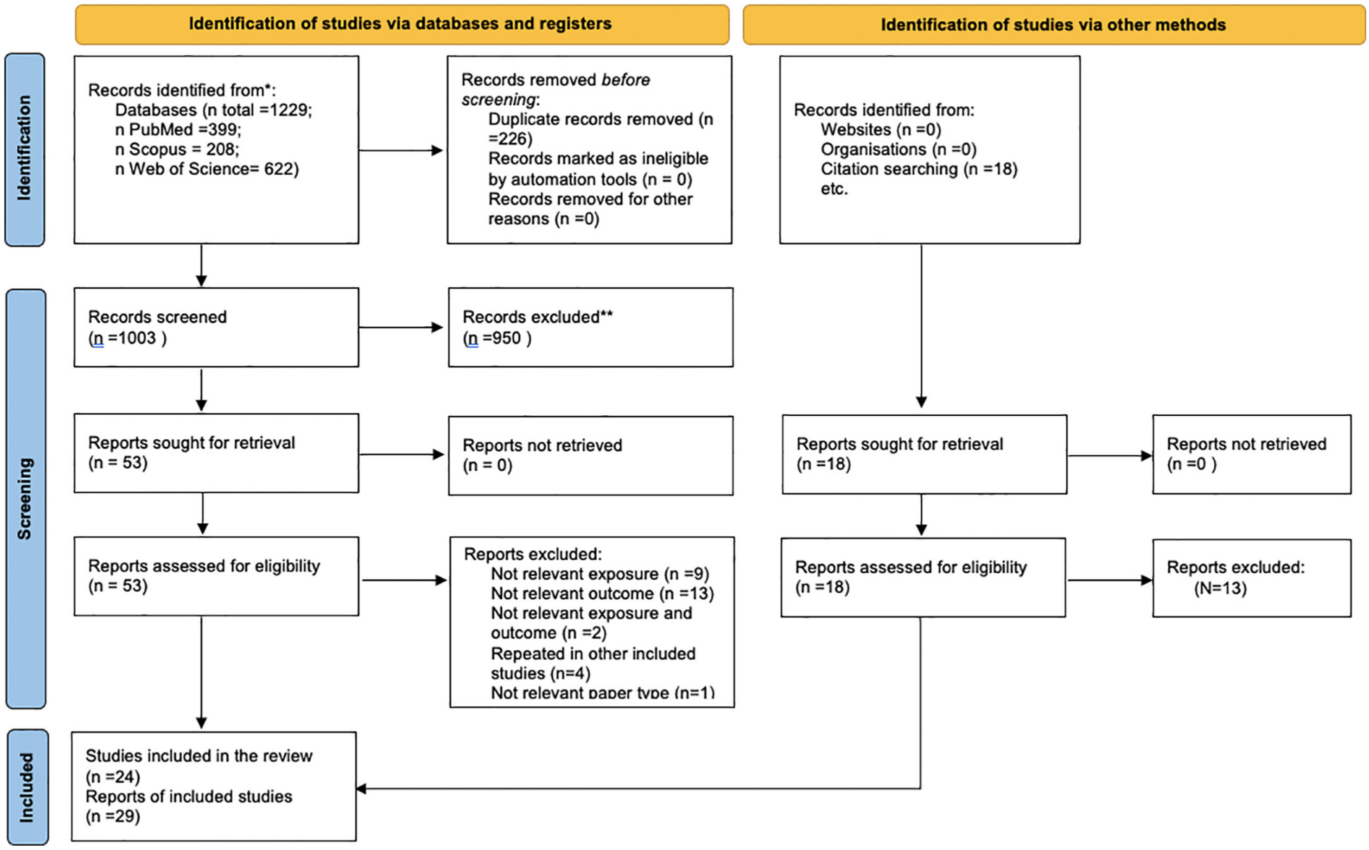

Fig. 1. PRISMA 2020 flow diagram for the systematic reviews on the association between exposure to greenspace and behavioral problems in children. *Note*: From: Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ 2021;372: n71. doi: https://doi.org/10.1136/bmj.n71.

(including: "very good " for NOS score ≥8, "good "for NOS score six or seven; "fair "for NOS score four or five, and "poor "for NOS score <4) (Sakhvidi et al., 2020). The ROB evaluation was performed by two reviewers (M.Z and A.M), and in the case of disagreement, the third reviewer (P.D) resolved the disagreement.

2.7. Effect measures

We extracted the reported associations (e.g. relative risk (RR), hazard ratio (HR), odds ratio (OR), incidence rate ratio (IRR), standardized incidence ratio (SIR), or correlation coefficient) and their corresponding confidence intervals as the acceptable effect sizes in this study. In the case of reporting crude and adjusted associations for specific exposure-outcome pairs, we preferred the most complete adjusted one which did not include the mediators in the model.

2.8. Synthesis methods

Because of the small number of studies, heterogeneity in outcome assessment and reporting, and also using different exposure measures which were not feasible to convert to each other, we were unable to perform a meta-analysis. Instead, we reported the proportion of significant protective/detrimental, suggestive for protective/ detrimental association and null associations for each outcome for the description of the findings.

3. Results

3.1. Study selection

We identified 1229 articles through databases search. After duplicate removal, 1003 items were retained and entered into the title and abstract screening step. At the end of the title and abstract screening step, we reached 53 articles. The full texts were checked based on the inclusion and exclusion criteria for eligibility to enter into the review; 29 of the articles were excluded and 24 of them were retained. Table S6 gives the exclusion reason of the articles at this step. We also found 18 other articles after searching the references of the selected studies. From which we retained 5 articles. Finally, we included 29 studies (24 from databases searching and 5 from references search) on 1,234,721 children (ranging from 169 (Faber Taylor and Kuo, 2011) to 814,689 (Thygesen et al., 2020) children) in the review (Faber Taylor and Kuo, 2011; Liao et al., 2020; Amoly et al., 2014; Balseviciene et al., 2014; Putra et al., 2021; Thygesen et al., 2020; Andrusaityte et al., 2020; Baumgardner et al., 2010; Bijnens et al., 2020; Butler et al., 2012; Donovan et al., 2019; Feng and Astell-Burt, 2017a; Feng and Astell-Burt, 2017b; Flouri et al., 2014; Lee et al., 2019; Madzia et al., 2019; Markevych et al., 2018; Markevych et al., 2014; McEachan et al., 2018; Meidenbauer et al., 2019; Razani et al., 2015; Reyes et al., 2013; Richardson et al., 2017; Saez et al., 2018; Van Aart et al., 2018; Yang et al., 2019; Zach et al., 2016; Jimenez et al., 2021; Maes et al., 2021) (Fig. 1).

3.2. Study characteristics

From the 29 studies included in this review, 21 studies (72.4%) were conducted since 2015 onward (Liao et al., 2020; Putra et al., 2021; Thygesen et al., 2020; Andrusaityte et al., 2020; Bijnens et al., 2020; Donovan et al., 2019; Feng and Astell-Burt, 2017a; Feng and Astell-Burt, 2017b; Lee et al., 2019; Madzia et al., 2019; Markevych et al., 2018; McEachan et al., 2018; Meidenbauer et al., 2019; Razani et al., 2015; Richardson et al., 2017; Saez et al., 2018; Van Aart et al., 2018; Yang et al., 2019; Zach et al., 2016; Jimenez et al., 2021; Maes et al., 2021). The majority of the included studies (n = 17; 58.6%) were cross-sectional in design (Faber Taylor and Kuo, 2011; Liao et al., 2020; Amoly et al., 2014; Balseviciene et al., 2014; Andrusaityte et al., 2020; Bijnens et al., 2020; Butler et al., 2012; Feng and Astell-Burt, 2017b; Lee et al., 2019; Markevych et al., 2018; Markevych et al., 2014; McEachan et al., 2018; Meidenbauer et al., 2019; Razani et al., 2015; Reyes et al., 2013; Saez et al., 2018; Zach et al., 2016). Most of these cross-sectional studies were conducted in Europe (nine studies; three in Germany (Markevych et al., 2018; Markevych et al., 2014; Zach et al., 2016), two in Lithuania (Balseviciene et al., 2014; Andrusaityte et al., 2020), two in Spain (Amoly et al., 2014; Saez et al., 2018), one in Belgium (Bijnens et al., 2020), and one in the UK (McEachan et al., 2018)), followed by North America (five studies; all were conducted in the USA (Faber Taylor and Kuo, 2011; Butler et al., 2012; Meidenbauer et al., 2019; Razani et al., 2015; Reyes et al., 2013)), Asia (two studies; one in China (Liao et al., 2020), and another in South Korea (Lee et al., 2019)), and Oceania (one study in Australia (Feng and Astell-Burt, 2017b)). Of the 11 longitudinal studies (42.3%) that met inclusion criteria (Putra et al., 2021; Thygesen et al., 2020; Donovan et al., 2019; Feng and Astell-Burt, 2017a; Flouri et al., 2014; Madzia et al., 2019; Richardson et al., 2017; Van Aart et al., 2018; Yang et al., 2019; Jimenez et al., 2021; Maes et al., 2021), five were conducted in Europe (two in the UK (Flouri et al., 2014; Maes et al., 2021), one in Belgium (Van Aart et al., 2018), one in Denmark (Thygesen et al., 2020), and one in Scotland (Richardson et al., 2017)), three in Oceania (two in Australia (Putra et al., 2021; Feng and Astell-Burt, 2017a), and one in New-Zealand (Donovan et al., 2019)), two in North America (all in the USA) (Madzia et al., 2019; Jimenez et al., 2021), and one in China (Yang et al., 2019)). There was only one case-control study included in this review which was conducted in the USA (Baumgardner et al., 2010) (Fig. 2). Table 1 presents the general characteristics of the included studies.

3.3. Risk of bias

The overall quality of the studies in terms of risk of bias was fair (average quality score = 5.4 out of 9; ranging from 3 to 8), with two studies (6.9%) having a very good quality (Bijnens et al., 2020; Saez et al., 2018), 11 studies (38%) having a good quality score (Liao et al., 2020; Amoly et al., 2014; Putra et al., 2021; Thygesen et al., 2020; Donovan et al., 2019; Feng and Astell-Burt, 2017a; Lee et al., 2019; Richardson et al., 2017; Yang et al., 2019; Jimenez et al., 2021; Maes et al., 2021), 13 studies (44.8%) having fair quality score (Faber Taylor and Kuo, 2011; Putra et al., 2021; Andrusaityte et al., 2020; Baumgardner et al., 2010; Butler et al., 2012; Donovan et al., 2019; Feng and Astell-Burt, 2017b; Madzia et al., 2019; Markevych et al., 2018; Markevych et al., 2014; McEachan et al., 2018; Razani et al., 2015; Reyes et al., 2013; Richardson et al., 2017; Van Aart et al., 2018; Zach et al., 2016; Jimenez et al., 2021), and three studies (10.3%) having a poor quality score (Balseviciene et al., 2014; Flouri et al., 2014; Meidenbauer et al., 2019) (Tables 2–4). In three of the studies (regardless of the reported outcome) the effect sizes were not reported

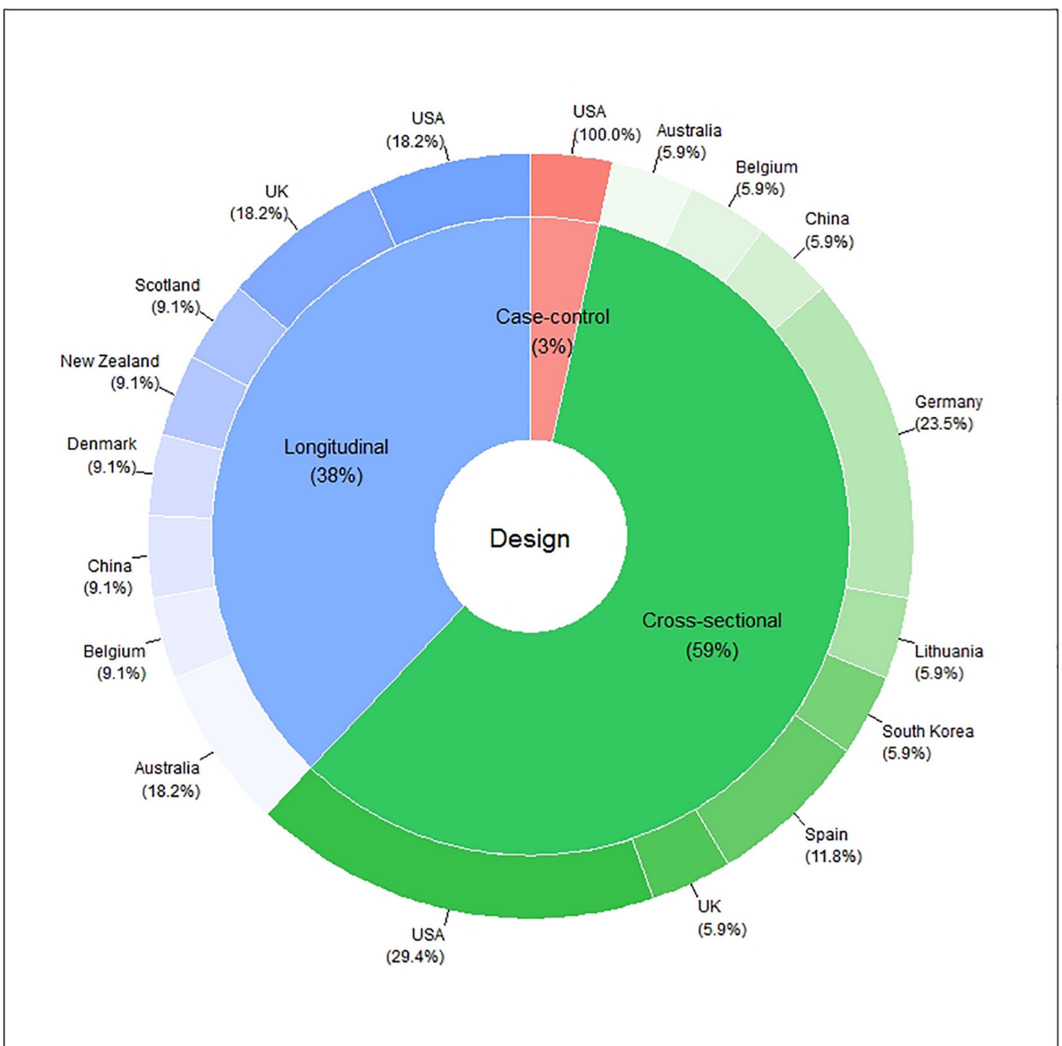

Fig. 2. Geographical distribution of studies according to the study design.

Table 1
Characteristics of the included studies in the review.

First author, year (country)	Design	Population (n)	Exposure	Outcome	Outcome assessment method	Risk of bias
Amoly et al., 2014 (Spain)	Cross-sectional	7–10 years old children (2111)	Use (Playing); Distance/Proximity; NDVI	Total difficulties; Hyperactivity/inattention and ADHD symptoms; Emotional symptoms; Conduct problems; Peer problems; Prosocial behavior	DSM-IV; SDQ	Good
Andrusaityte, et al., 2020 (Germany)	Cross-sectional	4–6 years old children (1489)	NDVI; Use (time)	Total difficulties; Hyperactivity/inattention and ADHD symptoms; Emotional symptoms; Conduct problems; Peer problems; Prosocial behavior	SDQ	Fair
Balseviciene et al., 2014 (Lithuania)	Cross-sectional	4–6 years old children (1468)	NDVI; Distance/Proximity	Total difficulties; Hyperactivity/inattention and ADHD symptoms; Emotional symptoms; Conditional problems; Peer problems; Prosocial behavior	SDQ	Poor
Baumgardner et al., 2010 (USA)	Case-control	5–17 years old children (case:6833, control:43630)	Distance/Proximity	ADHD diagnosis (done at primary care clinics)	ICD-9: 314.0–314.9	Fair
Bijnens et al., 2020 (Belgium)	Cross-sectional	7–15 years old children (620)	Percent coverage	Total difficulties; Externalize difficulties; Internalized difficulties	CBCL	Good
Butler et al., 2012 (USA)	Cross-sectional	6–17 years old children (64076)	Distance/Proximity	ADHD diagnosis	Parent report	Fair
Donovan et al., 2019 (New Zealand)	Longitudinal	From gestation until 18 years of old (49923)	NDVI	ADHD diagnosis (in hospital)	ICD-10: F90.9; or a child received two or more prescriptions of ADHD.	Good
Feng et al., 2017a (Australia)	Cross-sectional	12–13 years old children (3083)	Percent coverage	Total difficulties; Externalize difficulties; Internalized difficulties	SDQ	Fair
Feng et al., 2017b (Australia)	Longitudinal	4–5 years old children (4968)	Percent coverage	Total difficulties; Externalize difficulties; Internalized difficulties	SDQ	Good
Flouri et al., 2014 (UK)	Longitudinal	3–7 years old children (6384)	Percent coverage	Hyperactivity/inattention; Peer problems; Conduct problems; Emotional symptoms	SDQ	Poor
Jimenez et al., 2021 (USA)	Longitudinal	Birth −7 years old children (908)	NDVI	Total difficulties; Prosocial behavior; Externalize difficulties; Internalized difficulties	SDQ	Good
Lee et al., 2019 (South Korea)	Cross-sectional	7–17 years old Children (1817)	MSAVI	Total difficulties; Externalize difficulties; Internalized difficulties; Conduct problems; ADHD Symptoms	CBCL	Good
Liao et al., 2019 (China)	Cross-sectional	5–6 years old children (6039)	NDVI	Total difficulties; Hyperactivity/inattention; Prosocial behavior	CBCL	Good
Madzei et al., 2019 (USA)	Longitudinal	7 and 12 years old children (562)	NDVI	Hyperactivity/inattention; Conduct problems	BASC-2	Fair
Maes et al., 2021 (UK)	Longitudinal	Adolescents aged 12–14 years old (3568)	NDVI; Type of greenspace	Total difficulties	SDQ	Good
Markevych et al., 2014 (Germany)	Cross-sectional	10 years old children (1932)	NDVI; Distance/Proximity	Total difficulties; Hyperactivity/inattention; Emotional symptoms; Conduct problems; Peer problems	SDQ	Fair
Markevych et al., 2018 (Germany)	Cross-sectional	10–14 years old children (66823)	NDVI	ADHD diagnosis (based on outpatient data assessed by a child/adolescent psychiatrist, neuropediatrician, or psychotherapist)	ICD-10: F90	Fair
McEachan et al., 2018 (UK)	Cross-sectional	4 years old children (2594)	NDVI	Total difficulties; Externalize difficulties; Internalized difficulties; Prosocial behavior	SDQ	Fair
Meidenbauer et al., 2019 (USA)	Cross-sectional	4–11 years old (239)	Percent covered	Total difficulties; Hyperactivity/inattention; Emotional symptoms; Conditional problems; Peer problems; Prosocial behavior	SDQ	Poor
Putra et al., 2021	Longitudinal	4–15 years old (n = 4969)	Greenspace quality	Prosocial behavior	SDQ	
Razani et al., 2015 (USA)	Cross-sectional	6 years and older children (64076)		ADHD diagnosis; ADHD severity	Parent report	Fair
Reyes et al., 2013 (USA)	Cross-sectional	5–17 years old children (7954)	Distance/Proximity	ADHD diagnosis	ICD-9: 314.0–314.9	Fair
Richardson et al., 2017 (Scotland)	Longitudinal	4–6 years old children (2650)	Percent coverage	Total difficulties; Hyperactivity/inattention; Emotional symptoms; Conditional problems; Peer problems; Prosocial behavior	SDQ	Good
Saez et al., 2018 (Spain)	Cross-sectional	8 years old and younger children (5193)	Distance/Proximity; Percent coverage	ADHD diagnosis (by primary care physician)	ICD-10: F90.0, F98.8	Very good
Taylor et al., 2011 (USA)	Cross-sectional	Mean age of 9.6 years old children (169)	Use (Playing)	ADHD diagnosis; ADHD symptom severity (assessed by Physician, psychologist, or psychiatrist)	Parent claim of formally diagnosed with ADHD	Fair
Thygesen et al., 2020 (Denmark)	Longitudinal	From birth to age 5 years old children (814689)	NDVI	ADHD diagnosis (assessed by the child and adolescent psychiatrists)	ICD-10: F90x, F98.8	Good
Van Aart et al., 2018 (Belgium)	Longitudinal	6.7–12.2 years old children (172)	Percent coverage	Total difficulties; Hyperactivity/inattention; Emotional symptoms; Conditional problems; Peer problems; Prosocial behavior	SDQ	Fair

Table 1 (*continued*)

First author, year (country)	Design	Population (n)	Exposure	Outcome	Outcome assessment method	Risk of bias
Yang et al., 2019 (China)	Longitudinal	2–17 years old children (59754)	NDVI; SAVI	ADHD Symptoms	DSM-IV	Good
Zach et al., 2016 (Germany)	Cross-sectional	Pre-school children (6206)	Availability	Total difficulties; Hyperactivity/inattention	SDQ	Fair

NDVI: Normalized Difference Vegetation Index; ADHD: Attention Deficit Hyperactivity Disorder; DMS-IV: Diagnostic and Statistical Manual of Mental Disorders Fourth Edition; SDQ: Strengths and Difficulties Questionnaire; ICD: International Classification of Diseases; CBCL: Child Behavior Checklist; MSAVI: Modified Soil-Adjusted Vegetation Index; BASC-2: Behavior Assessment System for Children Second Edition; SAVI: Soil-Adjusted Vegetation Index.

completely (Balseviciene et al., 2014; Flouri et al., 2014; Meidenbauer et al., 2019). In the longitudinal studies (average score: 5.9) the ascertainment of exposure and the presentation of the results with models including the possible mediators (e.g. air pollution) were the weakest domains (considered only in one-third of the studies). The definition of a non-exposed cohort from the same community was the strongest item for the longitudinal studies (considered in all of the studies). In the cross-sectional studies, presenting the results with models including possible mediators, and comparability between respondent and non-respondents was the weakest item (considered in around 20% and 35% of the studies) (Tables 2–4).

3.4. Exposure assessment

The included studies with quantified estimates applied a variety of methods to assess exposure to greenspace, which could be classified into three main groups, including (i) availability in terms of surrounding greenness (which is a measure of greenspace quantity based on different indices including NDVI, Modified Soil-Adjusted Vegetation Index (MSAVI), Soil-Adjusted Vegetation Index (SAVI), and Vegetation Continuous Field (VCF)) (Liao et al., 2020; Amoly et al., 2014; Balseviciene et al., 2014; Thygesen et al., 2020; Andrusaityte et al., 2020; Donovan et al., 2019; Lee et al., 2019; Madzia et al., 2019; Markevych et al., 2018; Markevych et al., 2014; McEachan et al., 2018; Yang et al., 2019; Jimenez et al., 2021; Maes et al., 2021), or surrounding greenspace (percentage of greenspace) (Bijnens et al., 2020; Feng and Astell-Burt, 2017a; Feng and Astell-Burt, 2017b; Flouri et al., 2014; Meidenbauer et al., 2019; Richardson et al., 2017; Saez et al., 2018; Van Aart et al., 2018); (ii) accessibility (in terms of distance/proximity to the selected types of green spaces; presence or absence of greenspace at specific buffer size or asking about accessibility by questionnaire) (Amoly et al., 2014; Balseviciene et al., 2014; Baumgardner et al., 2010; Butler et al., 2012; Markevych et al., 2014; Reyes et al., 2013; Saez et al., 2018); and (iii) other indicators such as the use of green spaces (Faber Taylor and Kuo, 2011; Amoly et al., 2014; Andrusaityte et al., 2020), greenspace quality (Putra et al., 2021), or availability checking by questionnaire (Razani et al., 2015; Zach et al., 2016) (Tables 5, S7). Different buffer sizes from 50 m (Bijnens et al., 2020) up to 2000 m (Bijnens et al., 2020) were used across the retrieved studies to measure greenspace availability. From 14 studies that reported the measurements across the buffer sizes (Liao et al., 2020; Amoly et al., 2014; Balseviciene et al., 2014; Thygesen et al., 2020; Andrusaityte et al., 2020; Bijnens et al., 2020; Donovan et al., 2019; Lee et al., 2019; Madzia et al., 2019; Markevych et al., 2014; McEachan et al., 2018; Van Aart et al., 2018; Zach et al., 2016; Jimenez et al., 2021; Maes et al., 2021), in one study the buffer size has not been reported (Donovan et al., 2019) and in another study, the greenspace availability was measured at zip code area level (Markevych et al., 2018). All the studies with buffer size with determined size, used circular buffers, except for one study which used quadratic buffer shape (Thygesen et al., 2020). The most frequently used buffer sizes across the studies were 500, 100, and 300 m respectively (Table S7). Temporality between exposure and outcome assessment also is not considered in most of the studies (Table S8). Only a few studies considered past exposure to greenspace in their models.

In addition to different definitions of expressing exposure to greenspace (Table S7), different sources of data including land-use/land-cover maps (Amoly et al., 2014; Balseviciene et al., 2014; Baumgardner et al., 2010; Bijnens et al., 2020; Feng and Astell-Burt, 2017a; Feng and Astell-Burt, 2017b; Flouri et al., 2014; Markevych et al., 2014; Reyes et al., 2013; Richardson et al., 2017; Saez et al., 2018; Van Aart et al., 2018), satellite images (Liao et al., 2020; Amoly et al., 2014; Balseviciene et al., 2014; Thygesen et al., 2020; Andrusaityte et al., 2020; Donovan et al., 2019; Lee et al., 2019; Madzia et al., 2019; Markevych et al., 2018; Markevych et al., 2014; McEachan et al., 2018; Yang et al., 2019; Jimenez et al., 2021; Maes et al., 2021), questionnaires, constructed interviews or audits (about proximity, use, and quality) (Faber Taylor and Kuo, 2011; Amoly et al., 2014; Putra et al., 2021; Butler et al., 2012; Meidenbauer et al., 2019; Razani et al., 2015; Zach et al., 2016) were applied. Land-use/land-cover maps with different precisions were used to assess the proportion of land covered by different types of green space (e.g. park, agricultural, forest, private garden), or proximity to a specific type of green space (Table S7). Of studies relying on remote sensing surrounding greenness indices, 11 used Landsat images with a 30 × 30 m spatial resolution (Liao et al., 2020; Amoly et al., 2014; Balseviciene et al., 2014; Thygesen et al., 2020; Donovan et al., 2019; Lee et al., 2019; Madzia et al., 2019; Markevych et al., 2014; McEachan et al., 2018; Yang et al., 2019; Jimenez et al., 2021); one applied Moderate Resolution Imaging Spectroradiometer (MODIS) sensor images with a 250 × 250 m spatial resolution (Markevych et al., 2018), and one with Sentinel-2 with 10 me resolution images (Maes et al., 2021). The source of satellite data could not be identified in one study (Andrusaityte et al., 2020). Eleven out of 14 studies used surrounding greenness, reported the exposure based on the NDVI, and one rest reported the exposure based on MSAVI (Lee et al., 2019). SAVI (Yang et al., 2019) and VCF (Donovan et al., 2019) were reported in one study. One study used LiDAR (Light Detection and Ranging) data in addition to NDVI maps for differentiating woodlands from the

Table 2
Risk of bias assessment for the selected longitudinal studies in the review.

Study	PS1	PS2	PS3	PS4	C1	C2	O1	O2	O3	Total score
Donovan et al., 2019	0	1	0	0	1	1	1	1	1	6
Feng et al., 2017	1	1	0	1	1	0	1	1	1	7
Flouri et al., 2014	0	1	0	1	0	0	0	1	0	3
Jimenez et al., 2021	1	1	1	1	0	0	1	1	0	6
Madzei et al., 2019	1	1	1	0	1	0	0	1	0	5
Maes et al., 2021	0	1	1	1	1	1	1	1	0	7
Putra et al., 2021	1	1	0	1	1	0	1	1	0	6
Richardson et al., 2017	1	1	0	1	1	0	1	0	1	6
Thygesen et al., 2020	1	1	0	1	1	1	1		1	7
Van Aart et al., 2018	0	1	1	1	0	1	1	0	0	5
Yang et al., 2019	1	1	0	1	1	0	1	1	1	7

For details on each item description please see Table S5.

Table 3
Risk of bias assessment for the selected case-control studies in the review.

Study	PS1	PS2	PS3	PS4	C1	C2	O1	O2	O3	Total score
Baumgardner et al., 2010	1	1	0	0	1	0	1	0	1	5

For details on each item description please see Table S5.

Table 4
Risk of bias assessment for the selected cross-sectional studies in the review.

Study	PS1	PS2	PS3	PS4	C1	C2	O1	O2	Total score
Amoly et al., 2014	1	1	1	1	1	0	1	1	7
Andrusaityte et al., 2020	0	1	0	1	1	0	1	1	5
Balseviciene et al., 2014	0	1	0	1	0	0	1	0	3
Bijnens et al., 2020	0	1	1	1	1	1	2	1	8
Butler et al., 2012	0	1	0	1	1	0	1	1	5
Feng et al., 2017	0	1	0	1	1	0	1	1	5
Lee et al., 2019	1	1	1	1	0	1	1	1	7
Liao et al., 2019	1	1	1	1	1	0	1	1	7
Markevych et al., 2014	0	1	0	1	1	0	1	1	5
Markevych et al., 2018	1	1	1	0	0	0	1	1	5
McEachan et al., 2018	0	1	0	1	1	0	1	1	5
Meidenbauer et al., 2019	0	1	0	0	0	0	1	0	2
Razani et al., 2015	1	1	0	1	0	0	0	1	4
Reyes et al., 2013	1	1	0	1	0	0	2	0	5
Saez et al., 2018	1	1	1	1	1	0	2	1	8
Taylor et al., 2011	0	1	0	1	1	1	0	1	5
Zach et al., 2016	1	1	0	1	0	0	1	1	5

For details on each item description please see Table S5.

grasslands (Maes et al., 2021). One study used an audit, reporting the results based on the percentage of green land cover within an approximate half-mile distance from the participants' homes or schools (Meidenbauer et al., 2019).

3.5. Outcomes

In this review, we identified nine types of behavioral outcomes including (ordered according to the reporting frequency): total behavioral difficulties ($n = 16$) (Liao et al., 2020; Balseviciene et al., 2014; Andrusaityte et al., 2020; Bijnens et al., 2020; Feng and Astell-Burt, 2017a; Feng and Astell-Burt, 2017b; Lee et al., 2019; Markevych et al., 2014; McEachan et al., 2018; Meidenbauer et al., 2019; Richardson et al., 2017; Van Aart et al., 2018; Zach et al., 2016; Jimenez et al., 2021; Maes et al., 2021), ADHD symptoms and severity ($n = 15$) (Faber Taylor and Kuo, 2011; Liao et al., 2020; Amoly et al., 2014; Balseviciene et al., 2014; Andrusaityte et al., 2020; Flouri et al., 2014; Lee et al., 2019; Madzia et al., 2019; Markevych et al., 2014; Meidenbauer et al., 2019; Razani et al., 2015; Richardson et al., 2017; Van Aart et al., 2018; Yang et al., 2019; Zach et al., 2016), conduct problems ($n = 10$) (Amoly et al., 2014; Balseviciene et al., 2014; Andrusaityte et al., 2020; Flouri et al., 2014; Lee et al., 2019; Madzia et al., 2019; Markevych et al., 2014; Meidenbauer et al., 2019; Richardson et al., 2017; Van Aart et al., 2018), ADHD diagnosis ($n = 10$) (Faber Taylor and Kuo, 2011; Amoly et al., 2014; Thygesen et al., 2020; Baumgardner et al., 2010; Butler et al., 2012; Donovan et al., 2019; Markevych et al., 2018; Razani et al., 2015; Reyes et al., 2013; Saez et al., 2018), prosocial behavior ($n = 10$) (Liao et al., 2020; Amoly et al., 2014; Balseviciene et al., 2014; Putra et al., 2021; Andrusaityte et al., 2020; McEachan et al., 2018; Meidenbauer et al., 2019; Richardson et al., 2017;

Table 5
Detailed exposure assessment methods and exposure data sources in the included studies.

First author (year)	Type of exposure measure	Exposure data source
Amoly et al., 2014	NDVI; Proximity; Use (Time playing/spending)	Satellite image (Landsat 5, 30 × 30 m resolution); Ecological Map of Barcelona; Questionnaire
Andrusaityte et al., 2020	NDVI; Proximity; Use (Time spent in a city park)	Satellite (Unknown); Unknown map; Questionnaire
Balseviciene et al., 2014	NDVI; Proximity	Satellite image (Landsat 7, 30 × 30 m resolution); Spatial land cover map (Kaunas municipality, parks >1 ha)
Baumgardner et al., 2010	Proximity	Unclear
Bijnens et al., 2020	Percent coverage	Corine land cover, and Green Map of Flanders (1m^2 resolution)
Butler et al., 2012	Proximity	Parent-reported telephone survey
Donovan et al., 2019	NDVI; VCF	Satellite images (Landsat, 30 × 30 m resolution, meshblock)
Feng et al., 2017a	Percent coverage; Quality	Land use data (Australian Bureau of Statistics, parkland, meshblock level); Quality (by questionnaire)
Feng et al., 2017b	Percent coverage; Quality	Land use data (Australian Bureau of Statistics, parkland, meshblock level); Questionnaire
Flouri et al., 2014	Percent coverage	Land cover map (Generalized Land Use Database, accuracy: 10 m^2, neighborhood (LSOA) level)
Jimenez et al., 2021	NDVI	Satellite images (Landsat, 30 × 30 resolution)
Lee et al., 2019	MSAVI	Satellite images (Landsat 7, 30 × 30 resolution)
Liao et al., 2019	NDVI	Satellite images (Landsat 5, 30 × 30 resolution)
Madzei et al., 2019	NDVI	Satellite images (Landsat, 100 × 100 resolution)
Maes et al., 2021	NDVI Grassland Woodland	Satellite images (Sentinel-2, 10 × 10 resolution) LiDAR data (defined as <1 m height) LiDAR data(defined as >1 m height)
Markevych et al., 2014	NDVI; Proximity	Satellite images (Landsat5, 30 × 30 resolution) Bavarian land-use dataset (resolution <5 m)
Markevych et al., 2018	NDVI	Satellite images (MODIS, 250 m resolution)
McEachan et al., 2018	NDVI; Proximity; Satisfaction; Use; Availability	Satellite images (Landsat 5, 30 × 30 resolution); For proximity the data source was unclear; Questionnaire
Meidenbauer et al., 2019	Percent coverage	Survey
Putra et al. 2021	Quality	Parent rating on Likert scale
Razani et al., 2015	Availability	Questionnaire and audit on neighborhood amenities (4 yes/no questions)
Reyes et al., 2013	Proximity	Land use map (unknown source)
Richardson et al., 2017	Percent coverage	Land use map (Corine land cover)
Saez et al., 2018	Proximity; Percent coverage	Land use map (Catalonia Road Map (ICGC))
Taylor et al.2011	Use (Playing in nature)	Survey
Thygesen et al.2020	NDVI	Satellite images (Landsat, 210 × 210 m resolution)
Van Aart et al., 2018	Percent coverage	Corine land cover
Yang et al., 2019	NDVI; SAVI	Satellite (Landsat 5, 30 × 30 m resolution)
Zach et al., 2016	Unclear (availability or accessibility)	Questionnaire

NDVI: Normalized Difference Vegetation Index; VCF: Vegetation Continuous Fields; MSAVI: Modified Soil-Adjusted Vegetation Index; LiDAR: Light Detection and Ranging; MODIS: Moderate Resolution Imaging Spectroradiometer; ICGC: Institut Cartogràfic i Geològic de Catalunya; SAVI: Soil-Adjusted Vegetation Index.

Van Aart et al., 2018; Jimenez et al., 2021), emotional symptoms (n = 8) (Amoly et al., 2014; Balseviciene et al., 2014; Andrusaityte et al., 2020; Flouri et al., 2014; Markevych et al., 2014; Meidenbauer et al., 2019; Richardson et al., 2017; Van Aart et al., 2018), peer-relationship problems (n = 8) (Amoly et al., 2014; Balseviciene et al., 2014; Andrusaityte et al., 2020; Flouri et al., 2014; Markevych et al., 2014; Meidenbauer et al., 2019; Richardson et al., 2017; Van Aart et al., 2018), externalizing disorders (n = 6) (Bijnens et al., 2020; Feng and Astell-Burt, 2017a; Feng and Astell-Burt, 2017b; Lee et al., 2019; McEachan et al., 2018; Jimenez et al., 2021), and internalizing disorders (n = 5) (Feng and Astell-Burt, 2017a; Feng and Astell-Burt, 2017b; Lee et al., 2019; McEachan et al., 2018; Jimenez et al., 2021).

Different instruments were applied to characterize behavioral outcomes. In the studies that used questionnaires, the most commonly used instruments were: SDQ (n = 15) (Amoly et al., 2014; Balseviciene et al., 2014; Putra et al., 2021; Andrusaityte et al., 2020; Feng and Astell-Burt, 2017a; Feng and Astell-Burt, 2017b; Flouri et al., 2014; Markevych et al., 2014; McEachan et al., 2018; Meidenbauer et al., 2019; Richardson et al., 2017; Van Aart et al., 2018; Zach et al., 2016; Jimenez et al., 2021; Maes et al., 2021), the Child Behavior Checklist (CBCL) (n = 3) (Liao et al., 2020; Bijnens et al., 2020; Lee et al., 2019), and the Behavior Assessment System for Children-Second Edition (BASC-2) (n = 1) (Madzia et al., 2019). Six out of nine studies reported ADHD diagnosis based on the International Classification of Diseases codes (ICD-9 and ICD-10), without mentioning the method of diagnosis (e.g. medical diagnosis) (Thygesen et al., 2020; Baumgardner et al., 2010; Donovan et al., 2019; Markevych et al., 2018; Reyes et al., 2013; Saez et al., 2018). Moreover, one of these studies used prescription of one or more ADHD specific medications such as methylphenidate hydrochloride, atomoxetine, or dexamfetamine sulfate as an additional criterion for defining ADHD (Donovan et al., 2019). The three remaining studies defined ADHD diagnosis used the parent reports based on previous ADHD diagnosis of the child according to the Diagnostic and Statistical Manual of Mental Disorders, fourth edition (DSM-IV) criteria or questionnaire (Faber Taylor and Kuo, 2011; Butler et al., 2012; Razani et al., 2015). Hereafter we report the summary of results for each behavioral outcome.

3.6. Total behavioral difficulties

Sixteen studies (Liao et al., 2020; Balseviciene et al., 2014; Andrusaityte et al., 2020; Bijnens et al., 2020; Feng and Astell-Burt, 2017a; Feng and Astell-Burt, 2017b; Lee et al., 2019; Markevych et al., 2014; McEachan et al., 2018; Meidenbauer et al., 2019; Richardson et al., 2017; Van Aart et al., 2018; Zach et al., 2016; Jimenez et al., 2021; Maes et al., 2021) reported the association between exposure to greenspace and total behavioral difficulties; using SDQ (n = 13) (Amoly et al., 2014; Balseviciene et al., 2014; Andrusaityte et al., 2020; Feng and Astell-Burt, 2017a; Feng and Astell-Burt, 2017b; Markevych et al., 2014; McEachan et al., 2018; Meidenbauer et al., 2019; Richardson et al., 2017; Van Aart et al., 2018; Zach et al., 2016; Jimenez et al., 2021; Maes et al., 2021), or CBCL (n = 3) (Liao et al., 2020; Bijnens et al., 2020; Lee et al., 2019) (Table 1). Most of the studies were conducted in Europe (n = 10) (Amoly et al., 2014; Balseviciene et al., 2014; Andrusaityte et al., 2020; Bijnens et al., 2020; Markevych et al., 2014; McEachan et al., 2018; Richardson et al., 2017; Van Aart et al., 2018; Zach et al., 2016; Maes et al., 2021), then in North America (n = 2) (Meidenbauer et al., 2019; Jimenez et al., 2021), Oceania (both in Australia) (n = 2) (Feng and Astell-Burt, 2017a; Feng and Astell-Burt, 2017b), and Asia (n = 2) (Liao et al., 2020; Lee et al., 2019). Eleven out of 16 studies (64.7%) had cross-sectional design (Liao et al., 2020; Amoly et al., 2014; Balseviciene et al., 2014; Andrusaityte et al., 2020; Bijnens et al., 2020; Feng and Astell-Burt, 2017b; Lee et al., 2019; Markevych et al., 2014; McEachan et al., 2018; Meidenbauer et al., 2019; Zach et al., 2016), and the rest were longitudinal (Feng and Astell-Burt, 2017a; Richardson et al., 2017; Van Aart et al., 2018; Jimenez et al., 2021; Maes et al., 2021). While most of the studies used one type of greenspace exposure measure (n = 11) (Liao et al., 2020; Bijnens et al., 2020; Feng and Astell-Burt, 2017a; Feng and Astell-Burt, 2017b; Lee et al., 2019; McEachan et al., 2018; Meidenbauer et al., 2019; Richardson et al., 2017; Van Aart et al., 2018; Zach et al., 2016; Jimenez et al., 2021), five different types of greenspace exposure measures were used across these studies, including surrounding greenspace based on NDVI and MSAVI in nine studies (Liao et al., 2020; Amoly et al., 2014; Balseviciene et al., 2014; Andrusaityte et al., 2020; Lee et al., 2019; McEachan et al., 2018; Jimenez et al., 2021; Maes et al., 2021); surrounding green space (reported as percent of land cover with green space) in six studies (Bijnens et al., 2020; Feng and Astell-Burt, 2017a; Feng and Astell-Burt, 2017b; Meidenbauer et al., 2019; Richardson et al., 2017; Van Aart et al., 2018); distance/proximity to green space in three studies (Amoly et al., 2014; Balseviciene et al., 2014; Markevych et al., 2014); greenspace accessibility in one study (assessed by parent answer to accessibility of green space) (Zach et al., 2016), and use (reported as playing time in greenspace in two studies (Zach et al., 2016). Only five studies reported the results for more than one greenspace exposure measure (Amoly et al., 2014; Balseviciene et al., 2014; Andrusaityte et al., 2020; Markevych et al., 2014; Maes et al., 2021). Included papers had different overall quality scores from poor (Balseviciene et al., 2014; Meidenbauer et al., 2019; Zach et al., 2016) to good (Liao et al., 2020; Amoly et al., 2014; Bijnens et al., 2020; Feng and Astell-Burt, 2017a; Lee et al., 2019; Richardson et al., 2017; Jimenez et al., 2021; Maes et al., 2021), with 81% (n = 13) having fair or good quality (Liao et al., 2020; Amoly et al., 2014; Andrusaityte et al., 2020; Bijnens et al., 2020; Feng and Astell-Burt, 2017a; Feng and Astell-Burt, 2017b; Lee et al., 2019; Markevych et al., 2014; McEachan et al., 2018; Richardson et al., 2017; Van Aart et al., 2018; Jimenez et al., 2021; Maes et al., 2021). Most of the reported associations (25 out of 30 extracted association) were suggestive of the protective role of greenspace exposure on the total difficulties score (three reported associations were statistically significant protective). However, among four reported associations which were not suggestive for protective role of the greenspace, only one of them was significant.

3.7. ADHD symptoms and severity

From 15 unique studies (Faber Taylor and Kuo, 2011; Liao et al., 2020; Amoly et al., 2014; Balseviciene et al., 2014; Andrusaityte et al., 2020; Flouri et al., 2014; Lee et al., 2019; Madzia et al., 2019; Markevych et al., 2014; Meidenbauer et al., 2019; Razani et al., 2015; Richardson et al., 2017; Van Aart et al., 2018; Yang et al., 2019; Zach et al., 2016) included for ADHD symptoms, nearly 53% were conducted in European countries (n = 8) (Amoly et al., 2014; Balseviciene et al., 2014; Andrusaityte et al., 2020; Flouri et al., 2014; Markevych et al., 2014; Richardson et al., 2017; Van Aart et al., 2018; Zach et al., 2016), and the rest in North America (n = 4) (Faber Taylor and Kuo, 2011; Madzia et al., 2019; Meidenbauer et al., 2019; Razani et al., 2015), and Asia (n = 3) (Liao et al., 2020; Lee et al., 2019; Yang et al., 2019). Outcome assessments were mostly conducted by using SDQ (n = 9) (Amoly et al., 2014; Balseviciene et al., 2014; Andrusaityte et al., 2020; Flouri et al., 2014; Markevych et al., 2014; Meidenbauer et al., 2019; Richardson et al., 2017; Van Aart et al., 2018; Zach et al., 2016), followed by CBCL (n = 2) (Liao et al., 2020; Lee et al., 2019), DSM-IV criteria (n = 2) (Amoly et al., 2014; Yang et al., 2019), BASC-2 (n = 1) (Madzia et al., 2019), and report of symptoms by parents (by asking "Which has your child been diagnosed with: attention deficit disorder or ADHD?") (Faber Taylor and Kuo, 2011).

Different exposure measures including residential surrounding greenspace based on NDVI, SAVI and MSAVI (n = 8) (Liao et al., 2020; Amoly et al., 2014; Balseviciene et al., 2014; Andrusaityte et al., 2020; Lee et al., 2019; Madzia et al., 2019; Markevych et al., 2014; Yang et al., 2019); percent of land cover with green space (n = 3) (Flouri et al., 2014; Richardson et al., 2017; Van Aart et al., 2018); distance/proximity to green spaces (n = 4) (Amoly et al., 2014; Balseviciene et al., 2014; Markevych et al., 2014; Meidenbauer et al., 2019); greenspace accessibility for attending (n = 1) (Zach et al., 2016), and playing time in green spaces (n = 3) (Faber Taylor and Kuo, 2011; Amoly et al., 2014; Andrusaityte et al., 2020) were applied by these studies. Quality assessment ranked the studies from poor (Balseviciene et al., 2014; Flouri et al., 2014; Meidenbauer et al., 2019; Zach et al., 2016) to good (Liao et al., 2020; Amoly et al., 2014; Lee et al., 2019; Richardson et al., 2017; Yang et al., 2019). About 71% (n = 10) having fair or good quality (Faber Taylor and Kuo, 2011; Liao et al., 2020; Amoly et al., 2014; Andrusaityte et al., 2020; Lee et al., 2019; Madzia et al., 2019; Markevych et al., 2014; Richardson et al., 2017; Van Aart et al., 2018; Yang et al., 2019). Most of the reported associations were suggestive of a protective relationship of greenspace exposure with ADHD symptoms.

3.8. ADHD diagnosis

From 10 included studies on ADHD diagnosis (Faber Taylor and Kuo, 2011; Amoly et al., 2014; Thygesen et al., 2020; Baumgardner et al., 2010; Butler et al., 2012; Donovan et al., 2019; Markevych et al., 2018; Razani et al., 2015; Reyes et al., 2013; Saez et al., 2018), five were conducted in North America (all in the USA) (Faber Taylor and Kuo, 2011; Baumgardner et al., 2010; Butler et al., 2012; Razani et al., 2015; Reyes et al., 2013), four in Europe (Amoly et al., 2014; Thygesen et al., 2020; Markevych et al., 2018; Saez et al., 2018), and one in Oceania (Donovan et al., 2019). Most of the studies (n = 6) (Thygesen et al., 2020; Baumgardner et al., 2010; Donovan et al., 2019; Markevych et al., 2018; Reyes et al., 2013; Saez et al., 2018) carried out the outcome assessment based on different versions of ICD codes (ICD-9 (Baumgardner et al., 2010; Reyes et al., 2013) and ICD-10 (Thygesen et al., 2020; Donovan et al., 2019; Markevych et al., 2018; Saez et al., 2018)). One study did outcome assessment by parents report on clinical diagnosis of ADHD (Faber Taylor and Kuo, 2011). Associations were reported for different types of greenspace exposure measures including proximity/distance (n = 3) (Baumgardner et al., 2010; Reyes et al., 2013; Saez et al., 2018), greenspace based on NDVI (n = 3) (Amoly et al., 2014; Donovan et al., 2019; Markevych et al., 2018), percent of green space land cover (n = 1) (Saez et al., 2018), and playing time in green spaces (n = 1) (Faber Taylor and Kuo, 2011). The quality of the included studies was scored ranging from fair in four studies (Faber Taylor and Kuo, 2011; Baumgardner et al., 2010; Markevych et al., 2018; Reyes et al., 2013) to good in two studies (Amoly et al., 2014; Donovan et al., 2019) and very good in one study (Saez et al., 2018).

Three studies found a protective association between greenspace exposure and ADHD diagnosis (Amoly et al., 2014; Baumgardner et al., 2010; Markevych et al., 2018). In one study, all the associations were null (Reyes et al., 2013), and in the rest of the studies, the findings were different depending on the exposure definition, mostly inclined toward the protective role of this exposure.

3.9. Conduct/conditional problems

Ten studies reported the association between exposure to greenspace and conduct problems (seven were conducted in Europe (Amoly et al., 2014; Balseviciene et al., 2014; Andrusaityte et al., 2020; Flouri et al., 2014; Markevych et al., 2014; Richardson et al., 2017; Van Aart et al., 2018), two in North America (Madzia et al., 2019; Meidenbauer et al., 2019), and one in Asia (Lee et al., 2019)). Six out of the ten studies were cross-sectional and the remaining four were longitudinal (Flouri et al., 2014; Madzia et al., 2019; Richardson et al., 2017; Van Aart et al., 2018). Outcome was characterized by SDQ (n = 8) (Amoly et al., 2014; Balseviciene et al., 2014; Andrusaityte et al., 2020; Flouri et al., 2014; Markevych et al., 2014; Meidenbauer et al., 2019; Richardson et al., 2017; Van Aart et al., 2018), CBCL (n = 1) (Lee et al., 2019), and BASC-2 (n = 1) (Madzia et al., 2019). The associations were reported based on different measures including proximity/distance (n = 3) (Amoly et al., 2014; Balseviciene et al., 2014; Markevych et al., 2014), surrounding greenspace based on NDVI (n = 6) (Amoly et al., 2014; Balseviciene et al., 2014; Andrusaityte et al., 2020; Lee et al., 2019; Madzia et al., 2019; Markevych et al., 2014), percent of green space land cover (n = 4) (Flouri et al., 2014; Meidenbauer et al., 2019; Richardson et al., 2017; Van Aart et al., 2018), and time spending in green spaces or use (n = 2) (Amoly et al., 2014; Andrusaityte et al., 2020). Included studies had a wide range of qualities from poor in three studies (Balseviciene et al., 2014; Flouri et al., 2014; Meidenbauer et al., 2019) to good in two studies (Amoly et al., 2014; Lee et al., 2019). Among 19 extracted associations, none of them were significant, and 10 of the associations were suggestive for the increase in the conduct problems with an increase in greenspace exposure. Nine of the associations were suggestive of the protective role of greenspace for conduct problems.

3.10. Prosocial behavior

We found 10 unique studies that reported the results for prosocial behaviors (Liao et al., 2020; Amoly et al., 2014; Balseviciene et al., 2014; Putra et al., 2021; Andrusaityte et al., 2020; McEachan et al., 2018; Meidenbauer et al., 2019; Richardson et al., 2017; Van Aart et al., 2018; Jimenez et al., 2021). Nine of them (Amoly et al., 2014; Balseviciene et al., 2014; Putra et al., 2021; Andrusaityte et al., 2020; McEachan et al., 2018; Meidenbauer et al., 2019; Richardson et al., 2017; Van Aart et al., 2018; Jimenez et al., 2021) used SDQ, and one study applied CBCL (Liao et al., 2020) to characterize prosocial behavior. Six out of 10 studies were cross-sectional (Liao et al., 2020; Amoly et al., 2014; Balseviciene et al., 2014; Andrusaityte et al., 2020; McEachan et al., 2018; Meidenbauer et al., 2019), and four remaining were longitudinal (Putra et al., 2021; Richardson et al., 2017; Van Aart et al., 2018; Jimenez et al., 2021). Associations were reported based on different exposure measures including proximity/distance (n = 2) (Amoly et al., 2014; Balseviciene et al., 2014), surround greenspace based on NDVI (n = 6) (Liao et al., 2020; Amoly et al., 2014; Balseviciene et al., 2014; Andrusaityte et al., 2020; McEachan et al., 2018; Jimenez et al., 2021), the percentage of green space (n = 3) (Meidenbauer et al., 2019; Richardson et al., 2017; Van Aart et al., 2018), time spent in green space or use (n = 2) (Amoly et al., 2014; Andrusaityte et al., 2020), and greenspace quality (Putra et al., 2021). The quality of the retrieved evidence ranged from poor (n = 2) (Balseviciene et al., 2014; Meidenbauer et al., 2019), fair (n = 3) (Andrusaityte et al., 2020; McEachan et al., 2018; Van Aart et al., 2018) (24), to good (Liao et al., 2020; Amoly et al., 2014; Putra et al., 2021; Richardson et al., 2017; Jimenez et al., 2021). Most of the extracted associations (13 out of 18) were suggestive of the positive role of greenspace exposure for prosocial behaviors, however, three of the associations were significant However four associations in one study (Balseviciene et al., 2014) were suggestive for negative role of greenspace.

3.11. Emotional problems

From the eight retrieved studies on the association between greenspace exposure and emotional problems (Amoly et al., 2014; Balseviciene et al., 2014; Andrusaityte et al., 2020; Flouri et al., 2014; Markevych et al., 2014; Meidenbauer et al., 2019; Richardson et al., 2017; Van Aart et al., 2018), five were cross-sectional (Amoly et al., 2014; Balseviciene et al., 2014; Andrusaityte et al., 2020; Markevych et al., 2014; Meidenbauer et al., 2019) and three were longitudinal (Flouri et al., 2014; Richardson et al., 2017; Van Aart et al., 2018) and all used SDQ to characterize the outcome. Studies were conducted in Europe (n = 7) (Amoly et al., 2014; Balseviciene et al., 2014; Andrusaityte et al., 2020; Flouri et al., 2014; Markevych et al., 2014; Richardson et al., 2017; Van Aart et al., 2018) and North America (n = 1) (Meidenbauer et al., 2019). These studies applied proximity/distance (Amoly et al., 2014; Balseviciene et al., 2014; Markevych et al., 2014), surrounding greenspace based on NDVI (Amoly et al., 2014; Balseviciene et al., 2014; Andrusaityte et al., 2020; Markevych et al., 2014), the percentage of green space (Flouri et al., 2014; Meidenbauer et al., 2019; Richardson et al., 2017; Van Aart et al., 2018), and the duration of using green spaces (Amoly et al., 2014; Andrusaityte et al., 2020) to characterize exposure to greenspace. Three of these studies had poor quality (Balseviciene et al., 2014; Flouri et al., 2014; Meidenbauer et al., 2019), three had fair quality (Andrusaityte et al., 2020; Markevych et al., 2014; Van Aart et al., 2018), and one had good quality (Amoly et al., 2014; Richardson et al., 2017). Results of the studies that applied percent of green space in a residential area or use of greenspace were suggestive for a protective association for emotional problems (Balseviciene et al., 2014; Andrusaityte et al., 2020; Flouri et al., 2014; Markevych et al., 2014; Richardson et al., 2017; Van Aart et al., 2018). Among 15 exposure-outcome pairs, more than half (eight associations) were suggestive for the beneficial role of greenspace (none of them was significant). Six associations were suggestive for the negative role of greenspace in children's behavior (none of them were significant).

3.12. Peer relationship problems

Association between exposure to greenspace and peer relationship problems was reported by eight studies (Amoly et al., 2014; Balseviciene et al., 2014; Andrusaityte et al., 2020; Flouri et al., 2014; Markevych et al., 2014; Meidenbauer et al., 2019; Richardson et al., 2017; Van Aart et al., 2018), all of which used SDQ for the outcome characterization, and most of which were conducted in Europe ($n = 7$) (Amoly et al., 2014; Balseviciene et al., 2014; Andrusaityte et al., 2020; Flouri et al., 2014; Markevych et al., 2014; Richardson et al., 2017; Van Aart et al., 2018) (the remaining one was conducted in North America (Meidenbauer et al., 2019)). Five studies were cross-sectional (Amoly et al., 2014; Balseviciene et al., 2014; Andrusaityte et al., 2020; Markevych et al., 2014; Meidenbauer et al., 2019) and three remaining were longitudinal (Flouri et al., 2014; Richardson et al., 2017; Van Aart et al., 2018). Three studies reported their results for proximity/distance (Amoly et al., 2014; Balseviciene et al., 2014; Markevych et al., 2014), four reported for the surrounding greenspace based on NDVI (Amoly et al., 2014; Balseviciene et al., 2014; Andrusaityte et al., 2020; Markevych et al., 2014), four based on the percentage of green space land cover (Flouri et al., 2014; Meidenbauer et al., 2019; Richardson et al., 2017; Van Aart et al., 2018), and two based on the time spending in green space or use (Amoly et al., 2014; Andrusaityte et al., 2020). Retrieved evidence was in a different range of qualities from poor in three studies (Balseviciene et al., 2014; Flouri et al., 2014; Meidenbauer et al., 2019) to good in two studies (Amoly et al., 2014; Richardson et al., 2017), the rest of the studies ($n = 3$) having a fair quality (Andrusaityte et al., 2020; Markevych et al., 2014; Van Aart et al., 2018). Among 13 reported associations, two-third of them were suggestive for the protective role of the greenspace exposure, however, only three of the associations were significant Four associations in two studies were suggestive for the negative role of greenspace (only one the associations was significantly suggestive).

3.13. Externalizing and internalizing disorders

Six studies (Bijnens et al., 2020; Feng and Astell-Burt, 2017a; Feng and Astell-Burt, 2017b; Lee et al., 2019; McEachan et al., 2018; Jimenez et al., 2021), including two longitudinal (Feng and Astell-Burt, 2017a; Jimenez et al., 2021), and four cross-sectional studies (Bijnens et al., 2020; Feng and Astell-Burt, 2017b; Lee et al., 2019; McEachan et al., 2018) reported the association between exposure to greenspace and internalizing and/or externalizing problems. Four of these studies used SDQ (Feng and Astell-Burt, 2017a; Feng and Astell-Burt, 2017b; McEachan et al., 2018; Jimenez et al., 2021) and two applied CBCL (Bijnens et al., 2020; Lee et al., 2019) to characterize the internalizing and/or externalizing problems. Three studies reported the results for percent of land cover (Bijnens et al., 2020; Feng and Astell-Burt, 2017a; Feng and Astell-Burt, 2017b; Lee et al., 2019; McEachan et al., 2018; Jimenez et al., 2021), and the remaining two reported for surrounding greenspace based on NDVI (McEachan et al., 2018; Jimenez et al., 2021) and MSAVI (Lee et al., 2019). Two of the studies had fair quality (Feng and Astell-Burt, 2017b; McEachan et al., 2018) and the four remaining had good quality (Bijnens et al., 2020; Feng and Astell-Burt, 2017a; Lee et al., 2019; Jimenez et al., 2021). All of the 12 extracted associations were suggestive of the beneficial role of greenspace on externalizing disorders (three of the associations were significant). Similarly, for internalizing disorders most of the reported associations (9 out of 12 reported associations) were suggestive of a protective role of greenspace exposure. In three studies also at least one significant protective association was found between greenspace exposure and internalizing disorders. Two associations were suggestive for the negative role of greenspace on externalizing disorders, none of them were significant.

4. Discussion

We conducted a systematic review of the available evidence on the association of greenspace exposure (only in the studies that greenspace was reported based on the quantified estimates) with behavioral development in children. Most of the available studies were conducted from 2015 onwards, were carried out in Europe, and had a cross-sectional design. In general, most of the available studies had fair and good quality. Nine different behavioral outcomes (mostly total difficulties measured by SDQ) were reported across the studies. Overall, the reported findings were suggestive of the potential association of the greenspace exposure with reduced risk of behavioral problems. However, diversity of exposure-outcome assessment and reporting prevented us from doing a meta-analysis.

4.1. Exposure assessment

Exposure to the greenspace in the reviewed studies was characterized based on different approaches and performance (in terms of temporal and spatial resolution), mostly at residential address locations. Few studies (Liao et al., 2020; Yang et al., 2019) reported associations for school or kindergarten greenspace or the mixing approach (constructing the mixed weighted index by combining home and school greenspace). Part of the heterogeneity in the findings of the studies could be due to differences in the exposure assessment and allocation approaches (for example, residential versus school). Additionally, most of the studies did not consider long-term exposure to greenspace. For example, exposure assessment focused on specific periods such as school-age could consequently overlook other potential windows of susceptibility such as prenatal and preschool periods, which could be relevant to behavioral development (Richardson et al., 2017; Dadvand et al., 2015). Exposure to greenspace during pregnancy and early years of age has been considered very scarcely. Only three studies in this review included the exposure during the pregnancy period or from birth in their exposure assessments (Bijnens et al., 2020; Donovan et al., 2019; Richardson et al., 2017). Accordingly, it is difficult to draw firm conclusions on the relevance of these potentially critical windows of exposure. As the plasticity of the child's brain is considerably higher in the first years of life, any environmental exposure, including greenspace, could induce changes in the developing brain. Richardson et al. (Richardson et al., 2017) findings suggest that any beneficial influences are more likely to occur at younger ages, whereas Donovan et al. (Donovan et al., 2019) findings imply a non-significant association between exposure during the early life (prenatal period to age two years) greenspace exposure and ADHD. As the time window of exposure to greenspace could be a determining factor in the observed associations, future longitudinal studies with repeated measurement of exposure from early life (pregnancy period and first years of life) by considering both long-term and short-term exposure to greenspace could shed light on possible different relevant windows of susceptibility to exposure and their role in the observed heterogeneities.

Most of the studies in this review used surrounding greenness and proximity to green spaces to measure exposure. Greenspace use and quality were merely considered in three reviewed studies (Amoly et al., 2014; Thygesen et al., 2020; Andrusaityte et al., 2020). The quality and type of greenspace can modify the observed health benefits of greenspace (McEachan et al., 2018; Richardson et al., 2017; Van Aart et al., 2018). Selection of appropriate dataset is necessary to achieve the best performance. The effectiveness of different greenspace measurement methods may vary according to the different types of greenspace. Additionally, the accuracy and effectiveness of greenspace dataset in estimating the exposure could depend on different factors including the data sources, spatial and temporal resolution, and classes of greenspace. Therefore, the most appropriate assessment method and dataset may vary in different datasets, different study areas and different outcomes (Liao et al., 2021). Associations between greenspace and health outcomes are also suggested to depend on the greenspace measurement method (Zhou et al., 2021). Surrounding greenspace has been suggested to be measured more accurately by NDVI, and land use categories may be less suitable for health outcomes (Zhou et al., 2021).

Reporting the results for different surrounding greenspace measures (e.g. NDVI, MSAVI, etc.), for different types of green space instead of merely relying on the abundance of vegetation regardless of their types, and taking account of quality characteristics of the green spaces in addition to their availability can increase the breadth of our understanding about the possible associations and underlying mechanisms in future studies (Knobel et al., 2021).

4.2. Outcome assessment

The majority of the included studies applied questionnaires/tools that were filled by parents and hence were prone to subjectivity. Applying objective measures for characterization of the outcomes including using computerized tests and neuroimaging techniques, implementing the assessment tools by professionals (e.g. pediatric psychologists or psychiatrists), or relying on more than one source (e.g. child, parents, and/or teachers) for questionnaires can decrease the likelihood of the outcome misclassification in future studies. Using different outcome assessment methods (self-administrated questionnaire, direct interview, or diagnosis/evaluation by healthcare professionals) can have different validity and reliability in characterizing the behavioral problems and introduce heterogeneity in the findings. However, at the same time, these different tools can provide information on different aspects of the behavioral problems and, as such, can complement each other in providing a robust assessment of the outcomes.

4.3. Effect modification, confounding, and mediation

The effect of the natural environment on health could be moderated by the factors such as socioeconomic status (SES) (Balseviciene et al., 2014) (e.g. parental education (Markevych et al., 2014)), sex (Markevych et al., 2014), ethnicity (McEachan et al., 2018), and the degree of urbanity, among others. In addition to demographical characteristics such as ethnicity, sex, and age, future studies also need to control their analyses for family history of behavioral problems and wider SES variables. In addition, to be a potential effect modifier for the association between the greenspace exposure and behavior, SES can also be an influential confounder for this association. As such, studies evaluating this association need to properly control their analyses for SES indicators at both household (e.g., parental education, income, employment status) and neighborhood (e.g., census-based indices of deprivation) levels to minimize the likelihood of the residual SES confounding. Our included articles mainly controlled the analyses for indicators of household SES without taking neighborhood SES into account, which remains an area for improvement in future studies. Most of the studies have not explained the mechanisms through the mediator's analyses. We recommend future studies to formally analyze the mediation role of air pollution, physical activity, obesity, and environmental microbiota in the association between greenspace exposure and behavior problems.

4.4. Underlying mechanisms

The mechanisms underlying health benefits of greenspace are yet to be established. Additionally it is not clear to what extent the available proposed mechanisms for the health benefits of greenspace could be applicable for each of the behavioral outcomes. In general, reducing stress, restoring attention, enhancing social cohesion, increasing physical activity, enriching microbial input from the environment, and mitigating exposure to urban-related environmental hazards such as air pollution, noise, and heat have been suggested to be involved in beneficial role of greenspace on health (Markevych et al., 2017; Dadvand and Nieuwenhuijsen, 2019; Mueller et al., 2020). According to the stress reduction theory, natural environments can cause an overall sense of emotional wellbeing and calming effect by regulating human emotional responses to the environment and lowering neurophysiological stress. Moreover "*attention restoration theory*" describes the positive effect of exposure to the natural environment through redirecting attention away from attentional tasks that are necessary for daily urban life (Lei, 2018). Supportive environments can also alleviate the effects of fatigue and restore mental acuity. Furthermore, while exposure to air pollution and noise has been associated with an increased risk of behavioral problems (Forns et al., 2016), greenspace could mitigate such exposures (Dadvand et al., 2012; Dadvand et al., 2018). Further to the aforementioned, indirect mediated pathways, greenspace could also directly influence neurodevelopment through promoting discovery, risk-taking, engagement, and control and mastery, inciting basic emotional states such as a sense of wonder and bolstering sense of self (Dadvand et al., 2015; Bowler et al., 2010; Kahn and Kellert, 2002; Kellert and Wilson, 1993).

The findings on the beneficial association of the greenspace exposure with ADHD outcomes could be explained by a number of pathways, including stress reduction, attention restoration theory, increase in physical activity and social cohesion, enrichment of the gut microbial diversity, and mitigation of hazardous environmental factors such as air pollution and noise (Nieuwenhuijsen, 2021). Stress can exacerbate ADHD symptoms (Combs et al., 2015). Therefore, environments that promote stress reduction could be beneficial for reducing ADHD symptoms (McCormick, 2017; Faber Taylor and Kuo, 2011). Inattention is one of the main criteria for ADHD diagnosis, and reports on the positive influence of the exposure to greenspace on improved attention could be discussed through attention-restoration theory, which, suggests that greenspace could induce restoration from mental fatigue caused by directed attention needed in everyday tasks (Stevenson et al., 2018). Studies have reported an association between the gut microbiota composition in infancy and subsequent behavioral outcomes (Loughman et al., 2020). Children with ADHD have been reported to have lower gut microbial diversity (Cenit et al., 2017). At the same time, surrounding greenspace has been reported to increase microbial diversity and alter human microbiota composition (Selway et al., 2020; Bowyer et al., 2021). Therefore, nature and greenspace exposure could be beneficial for behavioral development through the enrichment of the personal microbiota.

Exposure to environmental pollutants such as air and noise pollution has been reported to be associated with increased behavioral problems (Dadvand and Nieuwenhuijsen, 2019; Combs et al., 2015). Greenspace can mitigate exposure to these environmental pollutants (Stevenson et al., 2018; Loughman et al., 2020) and through this pathway it could improve children behavior.

4.5. Strength and limitations and future research directions

The reported associations for the exposure-outcome pairs were not sufficient to do a meta-analysis of the evidence. Even in the case of sufficient pairs of exposure-outcome, the use of different and non-convertible effect sizes prevent us to do a meta-analysis. Outcome assessment tools in the included studies were different, and the form of presentation of the results for the same instrument in some cases was different (e.g. use of cut-off for SDQ instead of reporting quantitative score). In addition, outcome definitions for the specific behavioral problem were different across the studies and different inclusion and exclusion criteria were applied for population and outcome definition across the studies, which reduced our ability to directly compare the results of the studies. The classification and diagnostic procedure of the outcomes are particularly important and diagnostic procedures should be given in more detail in future studies. Additionally, from the methodological point of view, we did not register the systematic review before conducting the review. However, we strictly adhered to the defined protocol for the review.

The available literature on the association of exposure to greenspace and children's behavior is nearly almost all coming from the North American and European courtiers. Low- and middle-income countries and more specifically African, South American, and Middle Eastern countries are underrepresented in the literature. None of our reviewed studies formally evaluated the potential mechanisms underlying their findings, which remain an open question to be evaluated by future studies. Shedding light on such mechanisms could support the causal nature of the associations observed by our reviewed studies. Considering different hypothetical pathways of greenspace on behavioral health, future studies suggested considering different indicators of exposure to greenspace which are relevant to different proposed mechanisms. For example, while residential proximity to or use of green spaces could be more relevant to physical activity, mitigating urban-related hazards surrounding greenspace could be more relevant. We found that most of the available studies used greenspace availability indicators (surrounding greenness, percentage of land cover) as a measure of exposure, however using other groups of greenspace exposure indicators such as greenspace accessibility, and especially the use of greenspace might be more appropriate to explore the possible association.

Given the small number of studies with comparable exposure and outcome metrics, we were not able to conduct meta-regression analyses to identify the outcome-specific sources of heterogeneity and compare these sources among different outcomes. This remains as an open question for the future reviews on this topic.

5. Conclusions

In this review, we found that existing literature points out a beneficial association between exposures to greenspace with several behavioral outcomes in children. However, the available evidence remains limited and non-conclusive for some behavioral outcomes. Of 29 studies included in this review, 17 reported cross-sectional associations, which had limited capacity in establishing causality. Additionally, we did not find any study from Africa or middle-east to which the findings in other regions might not be generalizable. Our findings highlight the importance of a change in school and living environments to enhance children's exposure to greenspace toward considering greenspace as one of the target elements in urban environmental planning. Further studies on the behavioral outcomes with currently scarce or non-conclusive findings such as bullying and aggressiveness are necessary. Further observational (longitudinal studies with multiple measures of exposure and repeated assessment of outcome) should be planned to investigate this association in different cities and urban contexts and disentangle the mechanisms that would help to understand this relationship.

CRediT authorship contribution statement

Mohammad Javad Zare Sakhvidi: Conceptualization; Methodology; Data curation; Software; Formal analysis; Visualization; Writing – original draft; Writing – review & editing.

Pablo Knobel: Conceptualization; Methodology; Data curation; Formal analysis; Writing – review & editing.

Mariska Bauwelinck: Conceptualization; Methodology; Data curation; Formal analysis; Writing – review & editing.

Carmen de Keijzer: Conceptualization; Methodology; Data curation; Formal analysis; Writing – review & editing.

Lilian Marie Boll: Conceptualization; Methodology; Data curation; Formal analysis; Writing – review & editing.

Giuseppina Spano: Conceptualization; Methodology; Data curation; Formal analysis; Writing – review & editing.

Monica Ubalde-Lopez: Conceptualization; Methodology; Data curation; Formal analysis; Writing – review & editing.

Giovanni Sanesi: Conceptualization; Methodology; Data curation; Formal analysis; Writing – review & editing.

Amir Houshang Mehrparvar: Methodology; Writing – review & editing.

Bénédicte Jacquemin: Conceptualization; Methodology; Writing – review & editing.

Payam Dadvand: Conceptualization; Methodology; Data curation; Software; Formal analysis; Visualization; Writing – review & editing.

Registration and protocol

The systematic review protocol was developed before initiation of the review, and all the review team members adhered to the protocol that was set at the beginning of the review. The review protocol has not been registered externally.

Support

The supporting bodies in this study had no role in hypothesis generation, data collection, analyses, interpretation and writing of the manuscript.

Availability of data, code and other materials

Data collection forms, and the data extracted from included studies are available upon the request from the corresponding author.

Human and animal rights and informed consent

This article does not contain any studies with human or animal subjects.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2022.153608.

References

Amoly, E., et al., 2014. Green and blue spaces and behavioral development in Barcelona schoolchildren: the BREATHE project. Environ. Health Perspect. 122 (12), 1351–1358.

Andrusaityte, S., et al., 2020. The effect of residential greenness and city park visiting habits on preschool Children's mental and general health in Lithuania: a cross-sectional study. Int. J. Hyg. Environ. Health 223 (1), 142–150.

Balseviciene, B., et al., 2014. Impact of residential greenness on preschool children's emotional and behavioral problems. Int. J. Environ. Res. Public Health 11 (7), 6757–6770.

Barton, J., Rogerson, M., 2017. The importance of greenspace for mental health. BJPsych Int. 14 (4), 79–81.

Baumgardner, D.J., et al., 2010. Geographic analysis of diagnosis of attention-deficit/hyperactivity disorder in children: eastern Wisconsin, USA. Int. J. Psychiatry Med. 40 (4), 363–382.

Bijnens, E.M., et al., 2020. Residential green space and child intelligence and behavior across urban, suburban, and rural areas in Belgium: a longitudinal birth cohort study of twins. PLoS Med. 17 (8), e1003213.

Bowler, D.E., et al., 2010. A systematic review of evidence for the added benefits to health of exposure to natural environments. BMC Public Health 10 (1), 1–10.

Bowyer, R.C., et al., 2021. Microbiota composition is moderately associated with greenspace composition in a UK cohort of twins. Sci. Total Environ. 813, 152321.

Butler, A.M., et al., 2012. The relationship of reported neighborhood conditions with child mental health. Acad. Pediatr. 12 (6), 523–531.

Cenit, M.C., et al., 2017. Gut microbiota and attention deficit hyperactivity disorder: new perspectives for a challenging condition. Eur. Child Adolesc. Psychiatry 26 (9), 1081–1092.

Clements, R., 2004. An investigation of the status of outdoor play. Contemp. Issues Early Child. 5 (1), 68–80.

Combs, M.A., et al., 2015. Perceived stress and ADHD symptoms in adults. J. Atten. Disord. 19 (5), 425–434.

Dadvand, P., Nieuwenhuijsen, M., 2019. Green space and health. Integrating Human Health Into Urban and Transport Planning. Springer, pp. 409–423.

Dadvand, P., et al., 2012. Surrounding greenness and exposure to air pollution during pregnancy: an analysis of personal monitoring data. Environ. Health Perspect. 120 (9), 1286–1290.

Dadvand, P., et al., 2015. Green spaces and cognitive development in primary schoolchildren. Proc. Natl. Acad. Sci. 112 (26), 7937–7942.
Dadvand, P., et al., 2018. The association between lifelong greenspace exposure and 3-dimensional brain magnetic resonance imaging in Barcelona schoolchildren. Environ. Health Perspect. 126 (2), 027012.
Data and Statistics on Children's Mental Health. [cited 2021 December 08]; Available from. https://www.cdc.gov/.
Donovan, G.H., et al., 2019. Association between exposure to the natural environment, rurality, and attention-deficit hyperactivity disorder in children in New Zealand: a linkage study. Lancet Planet. Health 3 (5), e226–e234.
Faber Taylor, A., Kuo, F.E., 2011. Could exposure to everyday green spaces help treat ADHD? Evidence from children's play settings. Appl. Psychol. Health Well Being 3 (3), 281–303.
Feng, X., Astell-Burt, T., 2017. Residential green space quantity and quality and child well-being: a longitudinal study. Am. J. Prev. Med. 53 (5), 616–624.
Feng, X., Astell-Burt, T., 2017. The relationship between neighbourhood green space and child mental wellbeing depends upon whom you ask: multilevel evidence from 3083 children aged 12–13 years. Int. J. Environ. Res. Public Health 14 (3), 235.
Flouri, E., Midouhas, E., Joshi, H., 2014. The role of urban neighbourhood green space in children's emotional and behavioural resilience. J. Environ. Psychol. 40, 179–186.
Forns, J., et al., 2016. Traffic-related air pollution, noise at school, and behavioral problems in Barcelona schoolchildren: a cross-sectional study. Environ. Health Perspect. 124 (4), 529–535.
Gregg, J.W., Jones, C.G., Dawson, T.E., 2003. Urbanization effects on tree growth in the vicinity of New York City. Nature 424 (6945), 183–187.
Higgins, J.P.T., et al., 2019. Cochrane Handbook for Systematic Reviews of Interventions. John Wiley & Sons.
Islam, M.Z., Johnston, J., Sly, P.D., 2020. Green space and early childhood development: a systematic review. Rev. Environ. Health 35 (2), 189–200.
Jimenez, M.P., et al., 2021. Early life exposure to greenness and executive function and behavior: an application of inverse probability weighting of marginal structural models. Environ. Pollut. 291, 118208.
Kahn Jr., P.H., Kellert Jr., S.R., 2002. Children and Nature: Psychological, Sociocultural, and Evolutionary Investigations. MIT press.
Kellert, S.R., Wilson, E.O., 1993. The Biophilia Hypothesis. Island Press.
Knobel, P., et al., 2021. Associations of objective and perceived greenness measures with cardiovascular risk factors in Philadelphia, PA: a spatial analysis. Environ. Res. 197, 110990.
Lee, M., Kim, S., Ha, M., 2019. Community greenness and neurobehavioral health in children and adolescents. Sci. Total Environ. 672, 381–388.
Lei, L., 2018. The effect of neighborhood context on children’s academic achievement in China: exploring mediating mechanisms. Soc. Sci. Res. 72, 240–257.
Liao, J., et al., 2020. Associations of exposure to green space with problem behaviours in preschool-aged children. Int. J. Epidemiol. 49 (3), 944–953.
Liao, Y., Zhou, Q., Jing, X., 2021. A comparison of global and regional open datasets for urban greenspace mapping. Urban For. Urban Green. 62, 127132.
Loughman, A., et al., 2020. Gut microbiota composition during infancy and subsequent behavioural outcomes. EBioMedicine 52, 102640.
Madzia, J., et al., 2019. Residential greenspace association with childhood behavioral outcomes. J. Pediatr. 207, 233–240.
Maes, M.J., et al., 2021. Benefit of woodland and other natural environments for adolescents’ cognition and mental health. Nat. Sustain. 4 (10), 851–858.
Markevych, I., et al., 2014. Access to urban green spaces and behavioural problems in children: results from the GINIplus and LISAplus studies. Environ. Int. 71, 29–35.
Markevych, I., et al., 2017. Exploring pathways linking greenspace to health: theoretical and methodological guidance. Environ. Res. 158, 301–317.
Markevych, I., et al., 2018. Outdoor air pollution, greenspace, and incidence of ADHD: a semi-individual study. Sci. Total Environ. 642, 1362–1368.
McCormick, R., 2017. Does access to green space impact the mental well-being of children: a systematic review. J. Pediatr. Nurs. 37, 3–7.
McEachan, R.R.C., et al., 2018. Availability, use of, and satisfaction with green space, and children's mental wellbeing at age 4 years in a multicultural, deprived, urban area: results from the born in Bradford cohort study. Lancet Planet. Health 2 (6), e244–e254.
Meidenbauer, K.L., et al., 2019. The gradual development of the preference for natural environments. J. Environ. Psychol. 65, 101328.
Morgan, R.L., et al., 2018. Identifying the PECO: a framework for formulating good questions to explore the association of environmental and other exposures with health outcomes. Environ. Int. 121 (Pt 1), 1027.
Mueller, M.A.E., Flouri, E., 2020. Neighbourhood greenspace and children's trajectories of self-regulation: findings from the UK millennium cohort study. J. Environ. Psychol. 71, 101472.
Mueller, W., et al., 2020. Urban greenspace and the indoor environment: pathways to health via indoor particulate matter, noise, and road noise annoyance. Environ. Res. 180, 108850.
Nations, U., 2014. World Urbanization Prospects: The 2014 Revision, Highlights. 32. Department of Economic and Social Affairs. Population Division, United Nations.
Nicole, W., 2018. Nature and neurodevelopment: differences in brain volume by residential exposure to greenness. Environ. Health Perspect. 126 (6), 064001.
Nieuwenhuijsen, M.J., 2021. New urban models for more sustainable, liveable and healthier cities post covid19; reducing air pollution, noise and heat island effects and increasing green space and physical activity. Environ. Int. 157, 1–8.
Ouzzani, M., et al., 2016. Rayyan—a web and mobile app for systematic reviews. Syst. Rev. 5 (1), 210.
Page, M.J., 2021. **PRISMA 2020** explanation and elaboration: **updated** guidance and exemplars for **reporting systematic reviews**. BMJ 372.
Parmes, E., et al., 2020. Influence of residential land cover on childhood allergic and respiratory symptoms and diseases: evidence from 9 European cohorts. Environ. Res. 183, 108953.
Putra, I., et al., 2020. The relationship between green space and prosocial behaviour among children and adolescents: a systematic review. Front. Psychol. 11, 859.
Putra, I.G.N.E., et al., 2021. Association between green space quality and prosocial behaviour: a 10-year multilevel longitudinal analysis of Australian children. Environ. Res. 196, 110334.
Raney, M.A., Hendry, C.F., Yee, S.A., 2019. Physical activity and social behaviors of urban children in green playgrounds. Am. J. Prev. Med. 56 (4), 522–529.
Razani, N., et al., 2015. Neighborhood characteristics and ADHD: results of a national study. J. Atten. Disord. 19 (9), 731–740.
Reyes, N., et al., 2013. The potential for sociocultural factors in the diagnosis of ADHD in children. WMJ 112 (1), 13–17.
Richardson, E.A., et al., 2017. The role of public and private natural space in children's social, emotional and behavioural development in Scotland: a longitudinal study. Environ. Res. 158, 729–736.
Roberts, H., et al., 2019. The effect of short-term exposure to the natural environment on depressive mood: a systematic review and meta-analysis. Environ. Res. 177, 108606.
Saez, M., et al., 2018. The association between exposure to environmental factors and the occurrence of attention-deficit/hyperactivity disorder (ADHD). A population-based retrospective cohort study. Environ. Res. 166, 205–214.
Sakhvidi, M.J.Z., et al., 2020. Air pollution exposure and bladder, kidney and urinary tract cancer risk: a systematic review. Environ. Pollut. 267, 1–13.
Selway, C.A., et al., 2020. Transfer of environmental microbes to the skin and respiratory tract of humans after urban green space exposure. Environ. Int. 145, 106084.
Stevenson, M.P., Schilhab, T., Bentsen, P., 2018. Attention restoration theory II: a systematic review to clarify attention processes affected by exposure to natural environments. J. Toxicol. Environ. Health B Crit. Rev. 21 (4), 227–268.
Taylor, A.F., Kuo, F.E., Sullivan, W.C., 2001. Coping with ADD: the surprising connection to green play settings. Environ. Behav. 33 (1), 54–77.
Thygesen, M., et al., 2020. The association between residential green space in childhood and development of attention deficit hyperactivity disorder: a population-based cohort study. Environ. Health Perspect. 128 (12), 127011.
US, E.P.A., 2021. What is Open Space/Green Space?. [cited 2021 October 10, 2021]; Available from. https://www3.epa.gov/region1/eco/uep/openspace.html
Van Aart, C.J.C., et al., 2018. Residential landscape as a predictor of psychosocial stress in the life course from childhood to adolescence. Environ. Int. 120, 456–463.
Vanaken, G.-J., Danckaerts, M., 2018. Impact of green space exposure on children’s and adolescents’ mental health: a systematic review. Int. J. Environ. Res. Public Health 15 (12), 2668.
Vlahov, D., Galea, S., 2002. Urbanization, urbanicity, and health. J. Urban Health 79 (1), S1–S12.
Wells, G.A., et al., 2000. The Newcastle-Ottawa Scale (NOS) for Assessing the Quality of Nonrandomised Studies in Meta-analyses Oxford.
Yang, B.-Y., et al., 2019. Association between greenness surrounding schools and kindergartens and attention-deficit/hyperactivity disorder in children in China. JAMA Network Open 2 (12) p. e1917862-e1917862.
Zach, A., et al., 2016. Association of sociodemographic and environmental factors with the mental health status among preschool children—results from a cross-sectional study in Bavaria, Germany. Int. J. Hyg. Environ. Health 219 (4–5), 458–467.
Zhou, Y., von Lengerke, T., Dreier, M., 2021. Comparing different data sources by examining the associations between surrounding greenspace and children's weight status. Int. J. Health Geogr. 20 (1), 1–13.