Associations between greenspace exposure and mental health and suicide: Evidence across the lifespan

Despina Bolanis

Educational and Counselling Psychology (ECP)

McGill University, Montreal

March 2024

A dissertation submitted to McGill University in partial fulfillment of the requirements for the degree of Doctor of Philosophy in School/Applied Child Psychology

Table of Contents

List of Tables and Figures

Abstract

There has been increasing attention in the last decade on the putative benefits of greenspace exposure (i.e., availability or contact with natural or semi-natural outdoor areas completely or partially covered by vegetation) for mental health and suicide-related outcomes across the lifespan. This dissertation is based on two published manuscripts in leading peer-reviewed journals (henceforth referred to as **Chapter 3** and **Chapter 4**) which aimed to extend the current state of knowledge on greenspace exposure and mental health and suicide by filling important gaps. First, the literature has been dominated by cross-sectional research designs which limits our ability to understand the long-lasting influence of greenspace exposure on mental health. Second, to the best of our knowledge, there has not yet been a systematic review that has evaluated the associations (if any) between greenspace exposure and suicide mortality, self-harm, and suicidal ideation. Third, the moderating roles of socioeconomic status and sex/gender have not been extensively evaluated. For instance, some research indicates that individuals experiencing socioeconomic disadvantage could benefit more from greenspace exposure (although such individuals often live in areas with less greenspace) than those that are more socioeconomically advantaged. Additionally, there is evidence suggesting that the positive associations of greenspace exposure with mental health may be different for males and females, highlighting the importance of further studying these differences. Fourth, most studies in the literature have not been consistent in controlling for key confounding variables at the individual, family, and neighborhood levels, making it imperative to adjust for such variables to help clarify the associations between greenspace exposure and mental health problem symptoms.

In response to these literature gaps, the aim of **Chapter 3** (*published in Science of the Total Environment, Impact Factor: 10.75*) was to systematically synthesize the available evidence on the associations between greenspace exposure and suicide-related outcomes, i.e.,

suicide mortality, self-harm, and suicidal ideation. Searches were executed in PsycINFO, MEDLINE, and Web of Science from inception up to January 6, 2023. In total, 23 studies met the inclusion criteria (n = 14 ecological designs, n = 4 cross-sectional designs, n = 3 longitudinal designs, and n = 2 experimental designs). All of the 23 included studies evaluated the associations between greenspace exposure and suicide-related outcomes in urban regions, while one study included additional analyses for these associations in a rural setting.

Protective associations of greenspace exposure were reported for suicide mortality (64%), self-harm (60%), and suicidal ideation (67%), with 36% of included studies not reporting a statistically significant association. Moreover, for studies stratified by sex, it was found that protective associations between greenspace exposure and suicide mortality were more salient for females (n = 7 studies) than for males (n = 4 studies). However, it was not possible to stratify results by socioeconomic status. In this review, experimental studies and studies using youth samples were rare.

In light of these findings, using the Québec Longitudinal Study of Child Development, **Chapter 4** (*published in Social Psychiatry and Psychiatric Epidemiology, Impact Factor: 4.52*) examined the prospective associations of residential greenspace exposure in childhood and suicidal ideation and other mental health problem symptoms such as inattention, hyperactivity/impulsivity, conduct problems, depression, and anxiety in adolescence. Data was collected from 742 urban-dwelling participants and childhood greenspace exposure was measured using the Normalized Vegetation Index (NDVI) within 250 m, 500 m, and 1000 m buffer zones surrounding the home residence. Childhood urban greenspace was associated with lower inattention problem symptoms for both females and males. Specifically, the results illustrated a 0.14 reduced standard deviation (β = - 0.14, SE = 0.05, p <0.001) in relation to an

interquartile range increase of NDVI at the 250 m buffer zone, and similar results were found in 500 m and 1000 m buffer zones. These associations only slightly attenuated after adjustment for individual, family, and neighborhood characteristics ($\beta = -0.13$, SE = 0.06, $p = 0.03$). No association was found for suicidal ideation and other mental health problem symptoms, and no moderation by sex or family socioeconomic status was noted.

Overall, the articles included in this dissertation have expanded our knowledge regarding the benefits of greenspace exposure and mental health across the lifespan. However, future studies are required to better comprehend the underlying mechanisms linking greenspace exposure to mental health, along with experimental studies that can help establish the causal influence of greenspace exposure in mitigating symptoms of mental health.

Résumé

Au cours de la dernière décennie, une attention croissante a été accordée aux bénéfices présumés de l'exposition aux espaces verts (c'est-à-dire la disponibilité ou le contact avec des espaces extérieurs naturels ou semi-naturels complètement ou partiellement recouverts de végétation) pour les problèmes de santé mentale et le suicide tout au long de la vie. Cette thèse est basée sur deux articles publiés dans des revues spécialisées de premier plan (désignés par la suite comme **Chapitre 3** et **Chapitre 4),** qui visaient à bonifier l'état actuel des connaissances sur l'exposition aux espaces verts et la santé mentale ainsi que le suicide en comblant d'importantes lacunes. Premièrement, la littérature a été dominée par des études transversale, ce qui limite notre capacité à comprendre l'association longitudinale de l'exposition aux espaces verts sur la santé mentale. Deuxièmement, à notre connaissance, il n'y a pas encore eu de revue systématique évaluant les associations (si elles existent) entre l'exposition aux espaces verts et la mortalité par suicide, les tentatives de suicides et les idéations suicidaires. Troisièmement, les rôles modérateurs du statut socioéconomique et du sexe/genre n'ont pas été largement évalués. Par exemple, certaines recherches indiquent que les personnes en situation de désavantage socioéconomique pourraient bénéficier davantage de l'exposition aux espaces verts (bien que ces personnes vivent souvent dans des zones avec moins d'espaces verts) que celles qui sont plus socioéconomiquement avantagées. De plus, des preuves suggèrent que les associations positives de l'exposition aux espaces verts avec la santé mentale peuvent être différentes pour les hommes et les femmes, soulignant l'importance d'étudier davantage ces différences. Quatrièmement, la plupart des études dans la littérature n'ont pas été cohérentes dans le contrôle des variables de confusion clés aux niveaux individuel, familial et du quartier, ce qui rend impératif d'ajuster ces variables pour aider à clarifier les associations entre l'exposition aux espaces verts et les problèmes de santé mentale.

En réponse à ces lacunes de la littérature, l'objectif du **Chapitre 3** (publié dans *Science of the Total Environment*, *Facteur d'impact : 10.75*) était de synthétiser systématiquement les preuves disponibles sur les associations entre l'exposition aux espaces verts et les résultats liés au suicide, c'est-à-dire la mortalité par suicide, les tentatives de suicides et les idéations suicidaires. Les recherches ont été effectuées dans PsycInfo, MEDLINE et Web of Science à partir de leur création jusqu'au 6 janvier 2023. Au total, 23 études répondaient aux critères d'inclusion (n = 14 écologiques, n = 4 transversales, n = 3 longitudinales et n = 2 expérimentales). Les 23 études incluses ont toutes évalué les associations entre l'exposition aux espaces verts et les résultats liés au suicide dans des régions urbaines, tandis qu'une étude comprenait des analyses supplémentaires pour ces associations dans les régions rurales. Une association protectrice de l'exposition aux espaces verts a été rapportée pour la mortalité par suicide (64 %), tentative de suicide (60 %) et l'idéation suicidaire (67 %), 36 % des études incluses ne rapportant pas d'association statistiquement significative. De plus, pour les études stratifiées par sexe, il a été constaté que les associations protectrices entre l'exposition aux espaces verts et la mortalité par suicide étaient plus marquées chez les femmes (n = 7 études) que chez les hommes (n = 4 études). Cependant, il n'était pas possible de stratifier les résultats par statut socioéconomique. Dans cette revue, les études expérimentales et les études utilisant des échantillons de jeunes étaient rares.

Compte tenu de ces résultats, en utilisant l'Étude longitudinale du développement des enfants du Québec (ELDEQ), le **Chapitre 4** (publié dans *Social Psychiatry and Psychiatric Epidemiology, Facteur d'impact : 4.52*) a examiné les associations prospectives de l'exposition aux espaces verts résidentiels dans l'enfance et les idéations suicidaires et d'autres symptômes de problèmes de santé mentale tels que l'inattention, l'hyperactivité/impulsivité, les problèmes de

conduite, la dépression et l'anxiété à l'adolescence. Les données ont été collectées auprès de 742 participants habitant en milieu urbain et l'exposition aux espaces verts en enfance a été mesurée à l'aide de l'indice de végétation normalisé (NDVI) dans des zones de 250 m, 500 m et 1000 m entourant le domicile. L'exposition aux espaces verts urbain durant l'enfance étaient associés à des problèmes d'inattention moindres chez les adolescents (aussi bien chez les filles que chez les garçons). Plus précisément, les résultats ont illustré une réduction de 0,14 écart-type (β = - 0,14, SE = 0,05, p <0.001) par rapport à une augmentation de l'écart interquartile du NDVI dans la zone de 250 m, et des résultats similaires ont été obtenus dans les zones de 500 m et 1000 m. Ces associations se sont légèrement atténuées après ajustement pour les caractéristiques individuelles, familiales et de quartier (β = - 0,13, SE = 0,06, p = 0.03). Aucune association n'a été trouvée pour les idéations suicidaires et les autres problèmes de santé mentale, et aucune association de modulation du sexe ou du statut socioéconomique familial n'a été notée.

Dans l'ensemble, les articles inclus dans cette thèse ont élargi nos connaissances sur les bénéfices de l'exposition aux espaces verts et de la santé mentale tout au long de la vie. Cependant, des études futures sont nécessaires pour mieux comprendre les mécanismes sous-jacents liant l'exposition.

Acknowledgements

The completion of this doctoral degree has been the most challenging yet rewarding venture I have embarked on to date. I credit the following individuals for helping me reach the finish line throughout all the highs and lows of my graduate school journey.

My deepest gratitude extends to my primary supervisor, Dr. Marie-Claude Geoffroy. You provided me with an opportunity to fulfill my longstanding dream of becoming a psychologist, during a time when entry into graduate school felt unattainable. Your uplifting energy, creative ideas, and enthusiasm for science has been a source of inspiration throughout my doctoral degree. Thank you for seeing my potential and for pushing me to develop my skills as a scientist. The research knowledge in suicide prevention and general scientific skills you have imparted in me are invaluable.

I would also like to extend my genuine thankfulness to my secondary supervisor, Dr. Bassam Khoury. Your kindness and support during a period of change and uncertainty are deeply appreciated. Your insight and guidance for my doctoral study (Chapter 3) has been invaluable. I would also like to thank my doctoral committee, Drs. Sylvana Côté and Éric Robitaille for their feedback which has greatly contributed to the published articles presented in this thesis. My appreciation also extends to all the collaborators that have contributed their time, expertise, and mentorship to the development of this research: Drs. Massimiliano Orri, Francis Vergunst, Suzanne Mavoa, Gustavo Turecki, Isabelle Ouellet-Morin, Frederick Phillipe, Vincent Paquin, and Mr. Alain Girard. To the members of the Youth Suicide Prevention Lab, thank you for providing me with support and a positive working environment which has been a meaningful factor in this journey. Furthermore, I would like to thank the participants of the Québec

Longitudinal Study of Child Development for their contribution to advancing scientific knowledge that extends beyond the content of this dissertation.

To my SACP cohort, we have seen each other laugh and cry (*and survived graduate school throughout a global pandemic together*). I have great admiration for all of you. It has been such a wonderful experience to be surrounded by a group of women who are not afraid to advocate for themselves and for their clients. We have supported one another throughout all our achievements and adversities. I hope we continue to keep in touch as the years go by. I am so excited to see all the incredible things we will continue to accomplish.

I am humbled by the boundless encouragement from my family and friends. To my parents, you instilled the belief in me that no dream was too big and always nurtured my curiosity. I am so grateful for your unconditional love, support, and encouragement. Becoming the first in our family's lineage to accomplish this academic milestone fills me with an overwhelming sense of pride, honour, and humility. This achievement is amplified by the support of our loved ones across generations. It isn't solely mine; it is a testament to the love, sacrifices, and dreams of the family members who came before me. To my younger sister and brother-in-law, your guidance and support have been invaluable. I am so fortunate for the endless laughter and hangouts which served as salient reminders of all the good that surrounds me, even on the more difficult days of this graduate school adventure (NPDC forever). To my in-laws, thank you for welcoming me into your family and for your understanding and support throughout this journey. To my friends, your presence has been a lifeline during the tumultuous phases of graduate school. You provided me with shoulders to lean on, a non-judgemental space to vent, offered advice and guidance, and celebrated my successes.

I am profoundly indebted to my husband, Christopher. Your love, patience, and unwavering belief in my abilities sustained me during the most arduous moments of this degree. We both immersed ourselves in simultaneous studies, balancing the rush of deadlines and life's demands in tandem. Thank you for standing by me, sacrificing alongside me, and being my pillar of support. Your presence throughout this journey has been a constant reminder of the life we are building together.

Last but certainly not least, I would like to thank all the youth and families I have had the privilege to work with who entrusted me with their stories, struggles, and triumphs. Each interaction with you has been a catalyst for my development as a psychologist. Your stories have provided me with lessons in empathy and fortitude, and each of you have helped me find my personal calling. This acknowledgement symbolizes the profound gratitude I hold for your trust, strength, and the invaluable role you have played in shaping my identity as a psychologist – dedicated to making a meaningful difference in the lives of others.

Contributions to Original Knowledge

The benefits of greenspace exposure for mental health have been documented in thousands of studies summarized in numerous systematic reviews and meta-analyses. While poor mental health can lead to suicidal ideation, self-harm, and even death by suicide, only few studies have documented associations of greenspace exposure with suicide-related outcomes, and no systematic review and meta-analysis has been conducted. To address this gap, we completed the first systematic review of the literature highlighting the associations between greenspace exposure and suicide-related outcomes across the lifespan. Although it was not possible to conduct a meta-analysis given the high heterogeneity of greenspace metrics used across studies, our findings illustrated that 64% of the associations between greenspace exposure and suicide, self-harm, and suicidal ideation were protective. Of note, none of the included studies focused on adolescent populations, with the vast majority of published studies on mental health having focused on adult populations. Adolescence is a key developmental period which coincides with the onset of mental health symptoms and suicidal ideation. To fill this gap, drawing from a large longitudinal dataset from the province of Québec, we found that increasing levels of childhood residential greenspace was associated with lower symptoms of inattention in adolescence. These findings are especially important as the literature in youth samples has been dominated by cross-sectional research designs. Conducting prospective population-based studies is imperative when examining the enduring associations between greenspace exposure and mental health as such designs allow for the assessment of individuals exposed to various levels of greenspace over longer follow up periods and provide the capacity to control for key confounding factors assessed prior to the exposure (e.g., childhood and parental mental health). Collectively, future work is needed to better understand the mechanisms that drive the associations between

greenspace exposure and mental health, in addition to experimental studies that can provide causal inferences regarding associations between greenspace exposure and mental health, which to date, have been widely drawn from observational research. Nonetheless, it is imperative to recognize that the findings from the published manuscripts in this dissertation offer further evidence that there is a protective association between greenspace exposure and attention in youth and suicidal risk across the lifespan.

Contribution of Authors

This dissertation consists of two published manuscripts: a systematic review and a longitudinal cohort study. The research questions, designs, and planned analyses were developed with the support of my supervisors. For both manuscripts, I was responsible for data processing, conducted all statistical analyses, fully drafted initial versions of the manuscripts, and am the first author on both manuscripts. Dr. Geoffroy along with all co-authors on these manuscripts contributed by supporting the interpretation of results and reviewing the manuscripts for important intellectual content. I was further supported by various research scholarships throughout my doctoral studies, including the Joseph-Armand Bombardier Canada Graduate Scholarship awarded by Social Sciences and Humanities Research Council (SSHRC), the Fonds Québécois sur la recherche en santé (FRQS) Doctoral Training Award (partially held), and Graduate Excellence Fellowship awarded by the Faculty of Education and Counselling Psychology at McGill University.

Chapter 1: Introduction

The role of the natural environment for the promotion of physical and mental health has gained significant research attention in the last decade (Hartig et al., 2014; J. Zhang et al., 2020). This is particularly relevant as challenges with mental health and suicide stand as prominent global public health concerns (World Health Organization, 2017a, 2022). Prioritizing the global mental health research agenda involves developing a better understanding of how features of the natural environment influence mental health across the lifespan (Collins et al., 2011; Patel et al., 2018; World Health Organization, 2021).

Along with lifestyle characteristics, such as physical activity, sleep, nutrition, diet, social connectedness, stress management, and the avoidance of risky substances, greenspace exposure (i.e., contact with nature) is gaining status as an essential feature of the environment for cultivating good physical and mental health (Firth et al., 2020; Sundermann et al., 2023). In fact, there is mounting evidence that greenspace exposure is associated with health across multiple domains. In regards to physical health, increased greenspace exposure has been associated with lower odds of obesity (Luo et al., 2020; Ye et al., 2022), improved cardiovascular health (Liu et al., 2022; Ye et al., 2022; Zhao et al., 2022), and slower epigenetic aging (Kim et al., 2023). Similarly, for mental health, increased greenspace exposure has been associated with less symptoms of common internalizing (e.g., depression, anxiety) and externalizing (e.g., Attention-Deficit Hyperactivity Disorder; ADHD, conduct problems) mental health problems (Liu et al., 2023; Y. Zhang et al., 2020), in addition to being associated with fewer feelings of loneliness and isolation (Astell-Burt et al., 2022).

Thus, a growing number of initiatives worldwide have been put in place to promote contact with the natural environment, particularly greenspaces (e.g., forests, parks) (Parks

Canada, 2014; Richardson et al., 2016). Such initiatives are typically centred around "nature prescribing" wherein licensed health care providers provide patients with written prescriptions to gain free access to and spend time in greenspaces (e.g., nature parks) (Kondo et al., 2020; Prescri-Nature, 2024; Reed et al., 2021). From a public health perspective, identifying modifiable protective factors that can help individuals cope with mental health problem symptoms and boost their well-being remains a top priority. Encouraging contact with greenspace holds the potential to benefit the general population from all socioeconomic backgrounds.

As such, investigations on the associations between greenspace exposure and mental health problem symptoms and suicide are warranted. However, there are several gaps that exist within the literature. First, the majority of studies included in reviews have been predominantly cross-sectional (Collins et al., 2020) which limits our ability to understand the long-lasting associations of greenspace exposure with mental health problem symptoms, as well as providing the capacity to control for key confounding factors that occur prior to the exposure. Second, associations have been well documented for common internalizing and externalizing mental health problem symptoms, with limited evidence regarding the potential beneficial associations with suicide-related outcomes (i.e., suicide mortality, self-harm, suicidal ideation) (Liu et al., 2023). Third, there is a paucity of knowledge regarding the associations between greenspace exposure and Canadian youth mental health, which is important as the onset of most mental health problem symptoms occurs by mid-adolescence (Solmi et al., 2022). Fourth, there have been noted differences in the benefits of greenspace exposure for different groups of individuals, such as for those from lower socioeconomic backgrounds (Balseviciene et al., 2014; De Vries et

al., 2020; De Vries et al., 2016) and disparities in these associations for females vs. males (Bolte et al., 2019; Núñez et al., 2022), although findings have been mixed.

Therefore, the overarching aim of this doctoral research was to bridge the aforementioned gaps by (**a**) systematically reviewing the evidence examining the associations between greenspace exposure and suicide-related outcomes across the lifespan (**Chapter 3**) and (**b**) evaluating the associations between childhood residential greenspace exposure and internalizing and externalizing adolescent mental health problem symptoms using a large population-based sample of Canadian Youth from the Canadian province of Québec, while accounting for key variables at the individual, family, and neighborhood levels (**Chapter 4**). The intention for this research was to inform on the associations between greenspace exposure and mental health and suicide, using a robust methodology, from the perspective of whole populations.

Chapter 2: Literature Review

2.1 Defining Mental Health

Mental health is an essential component of our overall health and is considered a fundamental human entitlement (World Health Organization, 2022). Maintaining good mental health enhances our capacity to connect, function effectively, cope with challenges, and flourish (World Health Organization, 2022). The spectrum of mental health is intricate, spanning from an ideal state of well-being to severe conditions characterized by substantial suffering and emotional distress (Patel et al., 2018; Tudor, 1996).

Well-being is defined as a state of contentment with low levels of distress and an overall good physical and mental health outlook (White, 2008). Conversely, The Diagnostic and Statistical Manual of Mental Disorders – 5th Edition – Text Revision (DSM-5-TR) defines a mental disorder as a clinically significant disturbance in cognitive, emotional, or behavioral functioning that reflects dysfunction in the psychological, biological, or developmental domains causing significant distress or disability (American Psychiatric Association, 2022). On the mental health spectrum, the most deleterious consequence of mental health symptomatology is suicide.

Indeed, the experience of mental health challenges varies in terms of intensity and distress, leading to potentially disparate social and clinical consequences (World Health Organization, 2022). Along this continuum, mental health problems manifest diversely and are perceived differently by individuals (Patel et al., 2018). For instance, conditions such as depression and anxiety may present as brief episodes of mild to moderate distress, that do not necessarily require professional follow-up to cope with symptoms (Tudor, 1996). However, these conditions can also manifest as severe and chronic conditions, necessitating intensive psychotherapy and pharmacological treatment (Tudor, 1996).

At any given moment, a varied combination of biopsychosocial and environmental factors may interact to either support or jeopardize mental health, influencing an individual's placement on the mental health spectrum (Marmot et al., 2008; Uher & Zwicker, 2017). Certain developmental periods hold greater significance than others in this regard. To illustrate, in a global meta-analysis of 192 epidemiological studies (n = 708, 561), it was found that the global onset of the first mental health problem occurred before the age of 25 years in 62.5% of the included individuals, with the peak age of onset being around 14.5 years for most disorders (e.g., neurodevelopmental, phobia, feeding/eating, mood) (Solmi et al., 2022). In fact, there was an additional peak age of onset that was identified in adulthood at around 30.5 years for mood, substance use, and stress-related disorders (Solmi et al., 2022). These results highlight that across the life course, it is imperative to promote mental health.

The distinctions regarding the mental health spectrum are important nuances to consider as the literature has evaluated the associations between greenspace exposure and a variety of mental health outcomes, including general well-being, internalizing and externalizing mental health problem symptoms, mental disorders, and suicide. As such, the literature covered below will draw from studies evaluating the full spectrum of mental health outcomes. Of note, the published articles included in this dissertation evaluate different areas of the spectrum: **Chapter 3** focused on suicide-related outcomes (i.e., suicide mortality, self-harm, and suicidal ideation) and **Chapter 4** focused on internalizing and externalizing mental health problem symptoms, including ADHD, conduct problems, depression, anxiety, and suicidal ideation.

2.2 Defining Greenspace Exposure

Historically, the term "nature" has been identified to encompass environments that have not been modified or influenced by human beings, including green and blue spaces (Bratman et

al., 2012). However, this definition represents one segment of a wide range of possible gradients, and the presence of "greenness" in a given landscape can be subject to cultural or personal interpretations (Buijs et al., 2009). For instance, across this gradient can include natural "green" environments such as forests, as well as "green" landscapes found in built environments including urban parks, street trees, or even indoor plants (Bratman et al., 2012; Hartig et al., 2014). Consequently, it is evident that what constitutes greenspace varies significantly depending on the environment under study. As opportunities to engage with greenspace, methods of experiencing it, and how greenspace availability differs across contexts, researchers have had to conceptualize greenspace in a way that encompasses these differences (Richardson et al., 2011).

As such, there is no current consensus on the definition of greenspace and such definitions vary across studies (Taylor & Hochuli, 2017). However, a broad definition of greenspace includes a natural or semi-natural outdoor area completely or partially covered by vegetation, including parks, forests, trees, natural gardens, meadows, and woodlands. More specifically, the concept of "greenspace exposure" refers to the availability or contact with greenspace in a given area (Labib et al., 2020a). This broad-band definition of greenspace exposure has been adopted in the current dissertation, to allow ease of interpretation across the literature presented.

2.3 Greenspace Exposure Metrics

Within the literature, there are a range of approaches that have been used to measure greenspace exposure (Labib et al., 2020b), which have been broadly categorized as objective and subjective (Chiabai et al., 2020; Y. Zhang et al., 2020).

Objective approaches aim to quantify greenspaces by using measurable, quantifiable data that provide unique information on the spatial patterns of the earth's surface (Bannari et al.,

1995). Specifically, these measures focus on the tangible and physical characteristics of greenspaces that humans can potentially encounter (Li & Sullivan, 2016; Nieuwenhuijsen & Khreis, 2019; Nutsford et al., 2013), including: (a) ***quantity*** (e.g., total amount of greenspace within a given area), (b) ***proximity*** (e.g., distance to greenspace), and (c) ***visibility*** (e.g., view of greenspace from a specific location or area). Capturing greenspace exposure through these categories is often done by defining specific areas (e.g., neighborhoods) around key locations like home addresses (Browning & Lee, 2017; Reid et al., 2018; Su et al., 2019). Buffer analyses (i.e., creating zones around map features based on distance) are then used to help indicate the varying degrees of "greenness" surrounding the defined areas (James et al., 2015; Markevych et al., 2017; Su et al., 2019). The greenspace metrics used for this approach include the Normalized Difference Vegetation Index (NDVI) and percentage of green cover which are generally extracted from remote sensing images, land cover map, and Google street view (Hystad et al., 2019; Labib et al., 2020a). There is also the use of the metric real time global positioning system (GPS) technology and geographic simulation to provide participants' daily locations and movement patterns (Henson et al., 2020; Lachowycz et al., 2012). All of these metrics are proxy measures for "greenness" and can produce different results for a given location and buffer distance (Browning & Lee, 2017; Jarvis et al., 2020; Labib et al., 2020a; Su et al., 2019). For instance, a recent systematic review (n = 45 studies) concluded that the statistical associations to childhood mental health depends to some extent on the greenspace metric used (Davis et al., 2021). Evidence was found for an association between the use of NDVI and internalizing and externalizing mental health problem symptoms, with the most consistent association for these outcomes in buffers of 100 m, 250 m, and 500 m surrounding a given area (e.g., residential address, school address, etc.) (Davis et al., 2021). These results echo those of a systematic review

of predominantly population-based adult samples (n = 59 studies) which highlighted that the most used greenspace metric was the NDVI (Labib et al., 2020b).

Additionally, there are several landscape metrics that offer a broader understanding of the spatial patterns and structures of a given landscape, including but not limited to vegetation (Rahimi et al., 2022; Turner, 1990). Such metrics focus on the degree to which a landscape is broken down into smaller, isolated patches or fragments due to human activities or natural processes (Rahimi et al., 2022; Turner, 1990). For instance, landscape metrics measure factors like patch density (i.e., number of greenspace patches in an area), clumpiness (i.e., proportion of area covered by greenspace), fragmentation (i.e., how scattered greenspace patches are), perimeter ratio (i.e., shape of greenspace), and mean patch area (i.e., average size of greenspace patches) (Mears et al., 2019; Uuemaa et al., 2009). These metrics provide a comprehensive understanding of greenspace by quantifying its structure and connectivity, ultimately guiding efforts to conserve, manage, and enhance greenspace within societies at large (Uuemaa et al., 2013).

On the other hand, ***subjective approaches*** aim to identify information regarding the experiences individuals have in greenspace, allowing them to express their perceptions and experiences, while also accumulating information via self-report and qualitative assessments. Typically, this consists of evaluating the quality (e.g., micro features or characteristics) and perceptions (e.g., perceived greenspace exposure and approximate vegetation density) of greenspace via questionnaires, understanding individual experiences in greenspace (e.g., thoughts/feelings, perceptions of safety) via in-depth interviews or surveys, or quantifying visits/activities (e.g., duration and frequency) carried out in greenspace (Akpinar, 2016; Hartig et al., 2014). More recently, the use of virtual reality has gained attention as a potential greenspace

exposure metric. There are various methods to virtually present green environments such as via high-definition television, 360-degree virtual reality, and computer-generated virtual reality (Yeo et al., 2020). The use of 360-degree virtual reality allows users to experience real, pre-recorded green environments in a panoramic view (Reece et al., 2022). On the other hand, computer generated virtual reality immerses users in simulated and artificial green environments (Reece et al., 2022). Virtual green environments have the potential to evoke a sense of presence and immersion in the green environment (Gorini & Riva, 2008; Riva et al., 2011), which may impact emotional responses (Diemer et al., 2015).

Indeed, while objective measures rely on quantitative and observable data, subjective measures capture individual experiences and perceptions related to greenspace exposure. The use of both types of measures provides a nuanced understanding of how greenspace exposure contributes to shaping physical and mental health. Together, these approaches provide opportunities for researchers to explore the multidimensional role greenspace plays in shaping human health.

2.4 Urban Greenspace

Urbanization is advancing swiftly worldwide, with over half of the global population currently residing in urban regions. Projections suggest that by 2030, six out of ten individuals will reside in cities, and this figure will climb to eight out of ten by 2050 (Rydin et al., 2012). The shift from rural to urban living significantly reduces access to greenspace (Skår & Krogh, 2009; Turner et al., 2004). This change also coincides with a noticeable increase in the worldwide prevalence of mental health problem symptoms (Ventriglio et al., 2021; Whiteford et al., 2013).

While urbanization has enhanced the health status of populations by providing improved career prospects, educational access, and better healthcare services (Vlahov & Galea, 2003; World Health Organization, 2017b), it has also introduced new health risks in rapidly expanding cities. These risks include heightened social disparities (Hartig & Kahn Jr, 2016), poor lifestyle habits like reduced physical activity and unhealthy diets (De Vries et al., 2011; Hartig et al., 2014), and the deterioration of the natural environment (World Health Organization Centre for Health Development, 2010). Consequently, these factors vis-à-vis urbanization may be associated with a range of physical and mental health conditions (Patil, 2014; Ventriglio et al., 2021). The collective health impact of urbanization is influenced by the vulnerability and resilience of particular populations, their capacity to adjust to environmental shifts, as well as how health services are structured and urban planning is carried out (Gianfredi et al., 2021). Therefore, the role of publicly available and accessible urban greenspaces is imperative, especially as they have been previously described as the "lungs of the city" (Jones, 2018). The body of research presented across **Chapters 3 and 4** underscores the significance of examining data sourced from urban regions, particularly considering the rapid rate of urbanization central to middle- and high-income regions.

2.5 Research Designs to Consider in Greenspace Exposure and Mental Health Literature

In the evolving literature of the greenspace exposure and mental health field, the methodological choices and research designs employed have implications for the depth and validity of our understanding of these associations. In consultation with previous systematic reviews (Liu et al., 2023; Vanaken & Danckaerts, 2018; Y. Zhang et al., 2020), it is evident that two categories of study designs have been employed when evaluating greenspace exposure and

mental health: (1) observational and (2) experimental designs, which have helped shape our current understanding.

Observational research designs involve the collection of data on participants without intervening or manipulating variables (Jablensky, 2002). Such designs are often employed to examine the associations between variables that occur in natural settings (Jablensky, 2002). Researchers do not impose interventions but rather observe the relations between exposure and outcome variables (Jablensky, 2002). More specifically, cross-sectional designs capture a snapshot of data at a single point in time. This can translate into evaluating concurrent levels of greenspace exposure and mental health outcomes. However, such designs cannot establish causation nor the long-term associations between prolonged greenspace exposure and mental health outcomes. Conversely, longitudinal research designs involve repeated observations of a sample of participants over an extended period of time (Jablensky, 2002). Longitudinal studies allow for the examination of changes in greenspace exposure and mental health outcomes over longer follow-up periods and provide the ability to control for key confounding factors assessed prior to the exposure. In this same line, ecological study designs have also been used in the literature (Nutsford et al., 2013; Vanaken & Danckaerts, 2018). These designs examine entire populations or communities, rather than relying on individual-level data (Jablensky, 2002). Such designs can explore how greenspace exposure (e.g., access, levels of greenness) at the population-level can be associated with mental health outcomes, providing valuable insights into community-level dynamics and the possibility to inform public health policies.

In contrast, experimental designs (i.e. randomized controlled trials) aim to investigate cause-and-effect relationships by manipulating independent variables to observe their effect on dependent variables, allowing researchers to draw conclusions about the impact of specific

interventions (Jablensky, 2002). Experimental or quasi-experimental study designs have been used to explore the effect of a prescribed activity in greenspace (e.g., walking, hiking, gardening) (Kotera et al., 2021) or evaluating the impact of a participant observing greenspace in person (with no other form of interaction) (Wen et al., 2019). Ideally, such studies are carried out in controlled or manipulated environments to determine the causal influence of greenspace on mental health outcomes.

Overall, both types of research designs are valuable in understanding the associations between greenspace exposure and mental health. In the current dissertation, the published studies draw predominantly on observational research designs as such designs hold the potential to inform associations based on whole populations.

2.6 Greenspace Exposure and Mental Health

In the last decade, there has been an increasing interest in investigating the associations between greenspace exposure and mental health. Indeed, the number of active journals covering greenspace and health research has increased significantly over time, from only 1 journal in 1901 to 943 in 2018 (J. Zhang et al., 2020). The multidisciplinary nature of this research area also contributes to the boost of published articles in this field, given that researchers from various disciplines (e.g., psychology, psychiatry, environmental sciences, urban planning, to name a few) come together to better understand greenspace exposure and mental health associations (J. Zhang et al., 2020). For instance, in 2019 alone, there were over 2000 articles published on the associations between greenspace exposure and mental health in peer-reviewed journals, with expected trends that the number of publications on this subject will continue to rise (J. Zhang et al., 2020). Additionally, definitions of greenspace exposure and the exposure metrics used in this

body of literature vary significantly. Consequently, in addition to the spike of interest in this field alongside the various definitions and metrics used, it becomes challenging to ascertain the current state of evidence regarding the benefits of greenspace exposure in promoting mental health.

Evidence from observational studies (objective greenspace exposure metrics)

Numerous systematic reviews have investigated the prospective associations between objective greenspace exposure measures and a wide range of mental health indicators (e.g., internalizing and externalizing symptoms, mental health disorders, suicide) in youth (Sakhvidi et al., 2022; Sprague et al., 2022; Vanaken & Danckaerts, 2018; Y. Zhang et al., 2020), adults (Geneshka et al., 2021; Liu et al., 2023; Van den Berg et al., 2015), and older adults (de Keijzer et al., 2020). Most of these reviews have concluded that there is a protective association between greenspace exposure and mental health problem symptoms, although the majority have combined both longitudinal and cross-sectional studies making it difficult to summarize their findings. This is due to inherent methodological differences in cross-sectional and longitudinal research, such as the consideration of temporal ordering, exposure levels, and selection of potential confounding factors which make it challenging to provide a unified summary across the breadth of literature.

In adults, a review of 21 observational (19% longitudinal, 81% cross-sectional) studies found that increased quantity of surrounding greenspace was associated with better reports of perceived mental health (i.e., as measured by general mental health questionnaires) (Van den Berg et al., 2015). These findings are in line with another review of 12 longitudinal studies in older adults which illustrated that long-term greenspace exposure was associated with reduced risk of stress, depression and anxiety symptoms, suggesting that long-term greenspace exposure

is conducive of healthy ageing (de Keijzer et al., 2020). Moreover, in a recent meta-analysis comprising of 18 studies and pooling data from more than 3,110,728 adults in the general population, it was found that a 10% increase in the proportion of greenspace was associated with a lower risk of depression and anxiety, and a 0.1 unit increase in NDVI was associated with a lower risk of depression (Liu et al., 2023). In youth, a recent review of 29 observational studies (39% longitudinal, 59% cross-sectional) identified that increased quantity of and proximity to greenspace was associated with fewer symptoms of internalizing (e.g., depression, anxiety) and externalizing mental health problems (e.g., ADHD) in children and adolescents aged up to 18 years (Sakhvidi et al., 2022), consistent with two other systematic reviews that evaluated these associations in youth up to 19 years (Y. Zhang et al., 2020) and 25 years (Vanaken & Danckaerts, 2018) .

However, in a systematic review investigating 40 longitudinal studies of adults from the general population (published in 2021), minimal evidence was found in support of increased surrounding greenspace quantity and accessibility as being associated with less symptoms of common mental health problems such as anxiety and depression (Geneshka et al., 2021). In contrast, in a systematic review comprised of longitudinal studies evaluating mental health (n = 13 studies) and attentional capacity (n = 7 studies) in youth aged 2 to 18 years, it was found that there was a protective association between greenspace exposure in toddlerhood/childhood and attention, along with a lower incidence of psychiatric disorders and conduct problems later in childhood and adolescence (Sprague et al., 2022).

Evidence from observational studies (subjective greenspace exposure metrics)

Understanding qualitative dimensions of greenspace perception builds upon the established associations noted between the level of greenness and quantity of greenspace and

mental health. Subjective greenspace exposure metrics used in observational studies typically involve providing participants with a questionnaire that assesses the extent to which they feel connected to greenspace or to provide information regarding perceived greenspace access. In a systematic review comprising of seven cross-sectional studies of adult samples, it was found that those who endorsed feeling connected to greenspace and who had a sense of care for greenspace self-reported higher scores of overall well-being (Houlden et al., 2018). Similarly, in a sample of 1895 Australian adults, it was found that those who perceived their neighborhood as having the highest level of greenness had 1.60 odds of better general mental health scores compared to those who had perceived their neighborhood as having the least level of greenness, over and beyond the influence of socioeconomic status (Sugiyama et al., 2008). In another study of 384 Turkish adolescents aged 13 to 19 years, participants completed a 15-item questionnaire that assessed various factors of restorative green environments (e.g., "When I am in greenspace, I feel free from what my parents and teachers want me to do") and they self-reported their previous two week mental health status (i.e., "very bad" to "very good") (Akpınar, 2021). The findings suggested that higher scores of perceiving greenspace as restorative was associated with higher scores of self-reported mental health status, while adjusting for sex, monthly income, and Body Mass Index (Akpınar, 2021).

Evidence from experimental studies (objective greenspace exposure metrics)

Experimental studies, such as randomized controlled trials, offer an opportunity to demonstrate causal relationships between experiences in nature (e.g., walking, hiking) and mental health. For instance, a meta-analysis comprising of seven randomized controlled studies in adult populations found that walking in greenspaces (in comparison to control conditions such as walking in an urban setting) was associated with a reduction in depressive and anxiety

symptoms (Grassini, 2022), corroborating with results from a recent systematic review (n = 4 randomized controlled trials, n = 10 within-subject and time-series designs with single group participants) which noted improvements in mood and decreases in rumination, anxiety, and stress following a nature-based, green-walking intervention (Ma et al., 2023). Together, these findings are in line with results from a single-blind randomized controlled trial conducted by our own research team (of which I was second co-author) wherein 47 adult patients from an outpatient clinic diagnosed with refractory Major Depressive Disorder were randomly assigned to complete a 60-minute walk in a forest park or urban setting (Watkins-Martin et al., 2021). Throughout this study, participants rated their positive and negative affect on six occasions: before the walk, during the walk, immediately after the walk, before bedtime, 24 hours, and 48 hours post-walk. We found that after controlling for baseline differences in affect, participants who walked in a forest park experienced lower levels of negative affect (but no difference in positive affect) compared to those who walked in an urban setting (Watkins-Martin et al., 2021). Interestingly, another study examined the impact of a nine week mountain hike program in a sample of 17 adult suicidal psychiatric patients, compared to a nine week control period during which patients received their usual treatment (i.e., psychotherapy and/or medication) (Sturm et al., 2012). The severity of suicidal ideation decreased from the beginning to the end of the hiking program, although there was also a decrease in suicidal ideation during the control period, albeit to a lesser extent. These results suggest that it is uncertain whether mountain hiking is more effective in reducing suicidal ideation compared to traditional treatment options. Taken together, there is evidence to suggest that experiences in greenspaces are beneficial for adult populations experiencing mental health problem symptoms.

However, in terms of the potential benefits of greenspace experiences on mental health in youth, the evidence is limited. One randomized controlled trial of children diagnosed with ADHD found that these children demonstrated better attentional abilities after completing a 20-minute walk in a park, in comparison to when they walked in a neighborhood setting (Faber Taylor & Kuo, 2009). Moreover, in a cross-over experiment, 64 adolescents aged 16 to 18 years demonstrated better concentration performance (evaluated via d2-R Test of Attention) and improved well-being after spending their lunch hour in a large green park or forest, in comparison to those who spent their time in a small green park (Wallner et al., 2018).

Evidence from experimental studies (subjective greenspace exposure metrics)

Some experimental studies (with very few randomized controlled trials) have sought to understand the effect of subjective and immersive greenspace experiences on mental health as well as collecting information based on interviews conducted with participants. For instance, a systematic review comprising of 21 experimental studies sought to determine whether virtual greenspace immersion (i.e., human-computer interaction via a head-mounted gear that displays captured media of greenspace and/or computer generated environments) was associated with positive benefits to psychological well-being (Frost et al., 2022). Of the included studies, 16 evaluated self-report measures of positive and negative affect while the remaining five studies evaluated physical indicators of stress (e.g., cortisol levels) (Frost et al., 2022). The results regarding virtual greenspace immersion and affect were mixed, with only seven studies reporting a significant reduction in negative affect, while eight studies either reported no change or an increase in negative mood following exposure to greenspace replicated in virtual reality (Frost et al., 2022). Of note, none of the studies included in this review consisted of youth samples. In another study, 14 adults from Bristol were instructed to take pictures during their walk in an

urban environment (Bornioli et al., 2018). Participants were then interviewed within 48 hours of their walk to elicit information on various feelings that were evoked during the walk (Bornioli et al., 2018). Thematic analysis revealed that the restorative potential of walking and affective experiences related to psychological well-being were primary themes associated with walking in an urban environment (Bornioli et al., 2018). While not all participants took pictures of urban greenspace during their walk, several of them did and reported positive feelings regarding the greenspace in the urban environment (Bornioli et al., 2018). Moreover, a sample of 24 American adolescents participated in three series of forest bathing (i.e., the practice of spending time in forested areas to invite healing interactions (Clifford, 2021) over a period of three weeks (Keller et al., 2023). The study consisted of a mixed-methods experimental design wherein adolescents completed a validated questionnaire (Warwick-Edinburgh Mental Well-Being Scale (Stewart-Brown et al., 2009) to assess their well-being on three occasions (before and after the first forest bathing experience and at the end of the three week forest bathing series) as well as completing open-ended surveys and journal entries (Keller et al., 2023). Quantitative results revealed that after one time of participating in forest bathing, baseline adolescent mental well-being scores improved post-forest bathing, suggestive of a moderate effect size (Keller et al., 2023). There was no significant difference in mental well-being whether adolescents participated in one versus three forest bathing experiences (Keller et al., 2023). Qualitative findings highlighted the restorative capacities of forests, along with feelings of gratitude, moment awareness, relaxation, and development of a clearer mind (Keller et al., 2023).

Rationale for evaluation of suicide-related outcomes

Indeed, numerous reviews have highlighted the protective role of greenspace exposure in reducing mental health problems (de Keijzer et al., 2020; Kotera et al., 2021; Mavoa et al.,

2019). Therefore, it appears plausible that similar benefits of greenspace exposure would be apparent in mitigating suicidal behaviors, especially since one of the most important contributors of suicide-related outcomes is mental illness (Turecki & Brent, 2016). For instance, approximately 90% of adults who die by suicide have a comorbid mental disorders, more commonly depression and substance abuse (Arsenault-Lapierre et al., 2004). Similarly, youth who have thought of or have attempted suicide concurrently experience depression, anxiety and/or disruptive mental disorders (Gili et al., 2019; Orri et al., 2020). Consequently, we should expect a parallel association between greenspace exposure and suicide-related outcomes.

2.7 Selection Effects of Greenspace

Selection effects related to greenspace exposure refer to the processes by which individuals self-select or are selected into environments with varying levels of greenspace (Oakes, 2004; Sampson et al., 2002). These factors can significantly influence, moderate, or confound the observed associations in studies examining the relation between greenspace exposure and mental health (Oakes, 2004; Sampson et al., 2002).

Effect Modification (i.e., Moderating Factors)

Moderating factors affect the strength or direction of the relationship between two other variables (Fritz & Arthur, 2017). Essentially, a moderating factor indicates when and under what conditions the association of one variable on another variable is stronger or weaker (Fritz & Arthur, 2017). In the context of greenspace exposure and mental health, several moderating factors have been consistently documented including socioeconomic status and sex/gender.

There are findings that indicate that greenspace might have the capacity to diminish health disparities linked to socioeconomic disadvantage (Brown et al., 2018; Browning & Lee, 2017; Mitchell & Popham, 2008). However, it has been noted that socioeconomically

disadvantaged individuals often have inadequate access and availability to greenspace, bringing forth an important environmental justice issue (Wolch et al., 2014). For instance, in a study comprising of the population of England (n = 40,813,236), it was found that the all-cause mortality (including self-harm) was higher for the most socioeconomically deprived in the least green areas compared to the least socioeconomically deprived in the most green areas (Mitchell & Popham, 2008). In parallel, it was found that in a sample of 249,405 elderly Americans, higher levels of neighborhood greenspace was associated with 37% lower odds of depression in low income neighborhoods, compared to 27% and 21% lower odds of depression in medium and high income neighborhoods, respectively (Brown et al., 2018). In a sample of 2909 Scottish children from various socioeconomic backgrounds, an interquartile increase in greenspace was associated with fewer peer problems for the socioeconomically disadvantaged and better prosocial behaviors for the most socioeconomically advantaged (Richardson et al., 2017). Additionally, this study revealed that a lack of access to a garden was associated with significantly higher levels of hyperactivity and conduct problems for the most socioeconomically disadvantaged children compared to the least socioeconomically disadvantaged (Richardson et al., 2017). However, socioeconomically advantaged individuals do not always have more access to or availability of greenspace. For instance, it was found that in Kansas City, although socioeconomically disadvantaged neighborhoods had a higher quantity of parks, they were of lower quality (Vaughan et al., 2013). In comparison, parks in socioeconomically advantaged neighborhoods had better aesthetics and more basketball courts (Vaughan et al., 2013). These results highlight that in addition to the unequal distribution of greenspace, the quality of greenspace can also be a source of environmental injustice (De Vries et al., 2020).

In addition to socioeconomic status, sex/gender may also modify the associations between greenspace and mental health. Three systematic reviews aimed to identify whether the benefit of greenspace exposure on health outcomes was more salient for females or males (Bolte et al., 2019; Núñez et al., 2022; Sillman et al., 2022). In the review by Bolte et al. (2019) (n = 7 studies), the authors evaluated the associations between greenspace exposure and self-rated health (i.e., physical and mental health outcomes combined), therefore, the direct results pertaining to mental health outcomes alone was not possible to ascertain. Regardless, the authors concluded that the potential effect modification by sex/gender on the association between greenspace and self-rated health was inconclusive, with some studies illustrating beneficial associations for only females, others for only males, and several studies highlighting beneficial associations for both. More recently, a systematic review (n = 16 studies) by Núñez et al. (2022) revealed that despite females lacking adequate access, proximity, and perceived safety in using greenspaces, the salutogenic effects of greenspace exposure on mental health was stronger for them compared to males, corroborating with results obtained in another systematic review (n = 62 studies) which demonstrated stronger associations for females regarding greenspace exposure and physical health outcomes (e.g., diabetes, obesity, cardiovascular disease) (Sillman et al., 2022).

Confounding Factors

Confounding factors are extraneous variables that correlate with both exposure and outcome variables, ultimately obscuring or distorting the true associations between exposure and outcome variables (Jager et al., 2008). Additionally, confounding factors must not be on the causal pathway between exposure and outcome variables, otherwise it would be considered as a potential mediating factor (Jager et al., 2008). Researchers strive to adjust for and understand

these factors to ensure that observed associations can be more accurately attributed to greenspace exposure itself rather than potentially overestimating or misinterpreting the role of greenspace exposure in its associations with mental health. Importantly, given the multidisciplinary nature of the environmental health field, it is crucial to adjust for factors that encompass not only individual characteristics, but also family/household and area level characteristics (Kabisch, 2019). Area-level characteristics refer to characteristics of the geographical area or neighborhood (e.g., socioeconomic status) that could influence the associations between greenspace exposure and mental health. Adjusting for characteristics at these three levels holds the potential to provide a robust understanding of the associations between greenspace exposure and mental health.

Within the greenspace and mental health literature, several systematic reviews have highlighted variables commonly controlled for at the individual, family/household, and area-levels, including sex, age, ethnicity, and socioeconomic status (Geneshka et al., 2021; Vanaken & Danckaerts, 2018; Y. Zhang et al., 2020). Although not commonly adjusted for in analyses, pre-existing mental health conditions may pose barriers to accessing or benefiting from greenspace. For instance, individuals with chronic and severe mental disorders may be less likely to make use of green areas, in comparison to healthier individuals who may select residential locations with more green areas, therefore increasing opportunities for healthy lifestyle habits, such as exercise (Cohen-Cline et al., 2015). It is also possible that those with severe mental illness reside in disadvantaged neighborhoods given socioeconomic disparities (Kivimäki et al., 2020). Indeed, pre-existing mental health problems hold the potential to influence the observed associations between greenspace exposure and current mental health problems, making such variables important factors to adjust for.

Researchers can select for potential confounding factors using various approaches such as narratively via extensive literature searches or using various techniques such as the Directed Acyclic Graph (DAG) (VanderWeele, 2019). A DAG is a non-parametric graphical representation of hypothesized causal assumptions (drawn from theory and expertise) that identify a minimal sufficient set of adjustment variables (based on the graphical structure) that aid in obtaining unbiased estimates (Greenland et al., 1999). However, although DAGs have an appeal to provide an objective method of identifying potential confounding factors, they also suffer from significant limitations; they result in complex visual models that are not necessarily more accessible than narrative explanations; they do not allow the representation of circular causality and loops; many readers have limited literacy in these models; and the algorithmic identification of the "minimal set of adjustment variables" assumes no measurement error (Suttorp et al., 2015; Tennant et al., 2021).

2.8 Mechanisms Involved in the Greenspace Exposure and Mental Health Associations

The biophilia hypothesis speculates that human beings have an inherent affinity for the natural environment (i.e., including greenspace) (Ulrich, 1993; Wilson, 1984). It posits that this intrinsic connection results in part from our genetic makeup and evolutionary history (Wilson, 1984). Recently, theoretical pathways linking greenspace exposure with mental health expand on this idea. These pathways delve into the intricate connections between greenspace exposure and various mental health outcomes, considering factors such as harm reduction, restoring capacities, and building capacities which ultimately drive the associations linking greenspace to mental health (Markevych et al., 2017; Zhang et al., 2021). In essence, the conceptual pathways (pioneered by Markevych et al. (2017) and more recently supported by (Zhang et al., 2021) that will be summarized below provide a multifaceted understanding of how our interaction with

greenspace influences health across the biological, psychological, and social domains (see **Figure 1**).

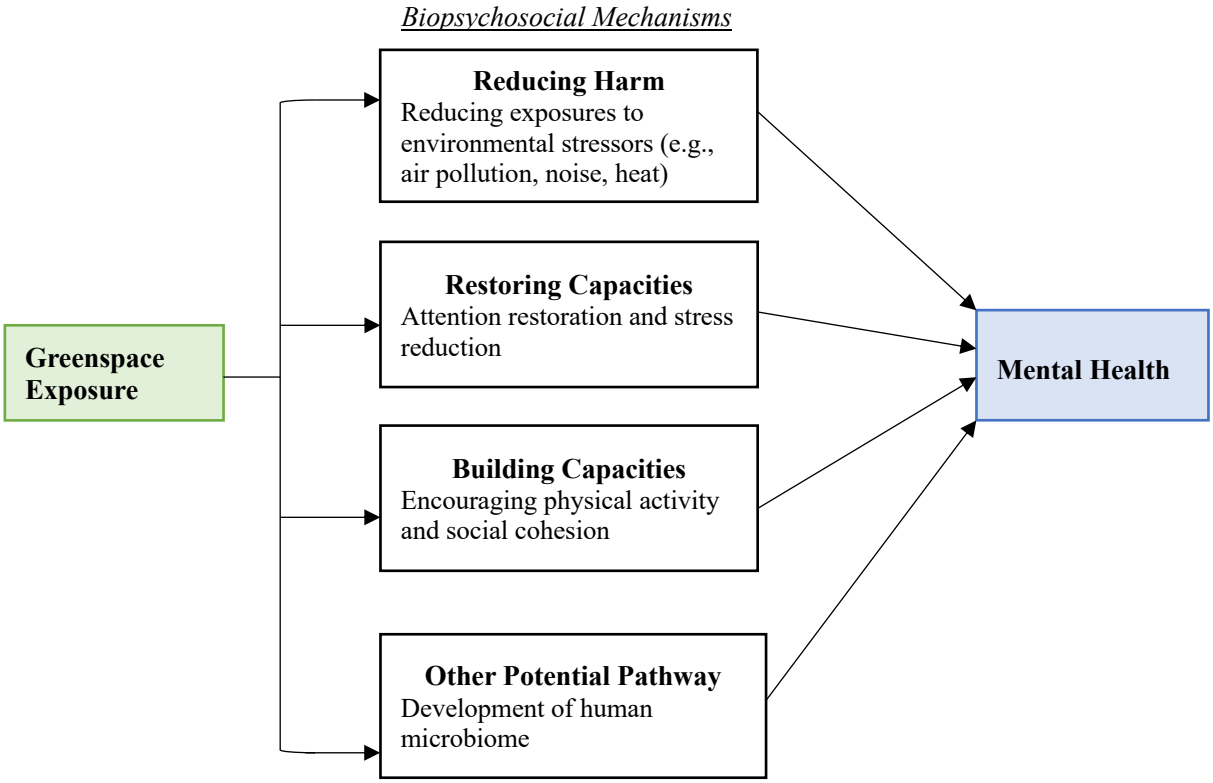


Figure 1. Theoretical pathways connecting greenspace exposure with mental health. Adapted from Markevych et al. (2017).

Reducing Harm

Emerging evidence suggests that mental health is impacted by rapidly occurring climate changes given the impact such changes have on air quality and other factors of built environments (Clayton, 2021; Cuijpers et al., 2023). To illustrate, in a meta-analysis comprising of nine studies, it was found that both long-term and short-term exposure to particulate matter was associated with higher odds of depression, anxiety, and suicide (Braithwaite et al., 2019). This is particularly alarming given that particulate matter is responsible for the largest proportion

of air pollution's health impacts (Manisalidis et al., 2020). However, studies have illustrated that air pollutant concentrations tend to be reduced in greenspace (Boudier et al., 2022; Hirabayashi & Nowak, 2016; Lei et al., 2021; Wang et al., 2022). For instance, neighborhoods and schools with higher levels of surrounding greenness have been documented to have lower air pollution exposures (Dadvand et al., 2012; Dadvand et al., 2015). Additionally, the rise in air temperatures in urban settings as a result of high-rise buildings, dense construction zones, and opaque surfaces (e.g., asphalt and concrete) is associated with both higher levels of air pollution as well as heat related mortality (Voogt & Oke, 2003; Yuan et al., 2019; Zhang et al., 2015). This is because there is a greater absorption and storage of solar energy in human made urban settings (Phelan et al., 2015). However, the presence of greenspace in such environments offers a cooling effect, improving the overall temperature (Byrne & Yang, 2009; Hamada & Ohta, 2010; Santamouris et al., 2018), and consequently human health. In parallel, greenspace can also buffer the effects of noise pollution (i.e., harmful levels of noise that impact human health) which is exacerbated in urban environments (Dzhambov & Dimitrova, 2014).

Restoring Capacities

There has been significant interest in greenspace exposure as a means for rejuvenating psychological capacities (Bratman et al., 2012; Hartig et al., 2014). In recent years, investigations into the revitalizing benefits of greenspace exposure have been shaped by two theories in environmental psychology: Stress Reduction Theory (SRT) and Attention Restoration Theory (ART).

The Stress Reduction Theory suggests that exposure to natural environments, such as greenspace, triggers rapid positive emotions, which counteract negative thoughts and emotions linked to stress (Ulrich, 1983; Ulrich et al., 1991). By tapping into biologically ingrained

responses to nature, this theory proposes that interactions with greenspace induces positive feelings, which reduces physiological stress responses, including hormonal changes and alterations in cardiovascular and musculoskeletal functions (Ulrich, 1983; Ulrich et al., 1991). This theory encourages the exploration of how greenspace exposure can lead to both reduced physiological activation and more positive self-reported emotions. To illustrate, in a sample of 25 adults from the United Kingdom, the authors examined the associations between percentage of surrounding residential greenspace and both objective (i.e., salivary cortisol) and subjective (i.e., self-reported perceived stress) stress measures (Thompson et al., 2012). The results revealed a significant and positive correlation between cortisol secretion and percentage of greenspace, as well as higher scores of perceived stress with decreasing quantity of residential greenspace (Thompson et al., 2012). In this same line, across two studies taking place in Japan (n = 12), participants were transported between forest and urban environments in order to determine the role of these environments on stress relief (via measures of salivary cortisol levels, diastolic blood pressure, and pulse rate), measured while participants were present in each environment (Lee et al., 2009; Park et al., 2007). The results showed a significant reduction on stress after just 15 minutes in the forest environment, which was not observed in the urban environment (Lee et al., 2009; Park et al., 2007).

On the other hand, the Attention Restoration Theory suggests that exposure to natural environments, such as greenspace, helps restore mental fatigue caused by directed attention tasks (i.e., consciously using cognitive resources to focus on a given stimulus) (Kaplan & Kaplan, 1989; Kaplan, 1995). By intrinsically captivating attention, greenspace enables neural networks associated with directed attention to recover, ultimately leading to reduced mental fatigue and enhanced cognitive abilities (Kaplan & Kaplan, 1989; Kaplan, 1995). For instance, in a meta-

analysis comprising of 17 experimental studies evaluating immersive and virtual greenspace exposures across youth and adult samples, it was found that greenspace exposure exerted a significant and positive effect on selective attention (Stevenson et al., 2018). Similarly, another systematic review aimed to synthesize the available evidence of short-term greenspace interventions and sustained attention and working memory in youth samples aged 5 to 18 years (Vella-Brodrick & Gilowska, 2022). The authors identified 11 studies that fit their inclusion criteria (e.g., experimental or quasi-experimental designs) and observed that greenspace interventions took place in the school setting or in indoor environments with plants, with differing intervention time durations and level of greenery involved (Vella-Brodrick & Gilowska, 2022). The significant results across these studies revealed that greenspace interventions improved sustained attention (n = 9 studies) and working memory (n = 2 studies) (Vella-Brodrick & Gilowska, 2022).

Overall, although each theory captures different restorative capacities of greenspace, they both presume that individuals who spend time in environments that promote rejuvenation (e.g., areas with more greenery) will experience greater mental health benefits over time compared to spending that same amount of time in less restorative environments (Hartig, 2007).

Building Capacities

Greenspace exposure has also been hypothesized to be linked with mental health by encouraging health-related behaviors such as physical activity and social cohesion. Greenspace offers opportunity for an accessible and attractive setting to conduct physical activity (Almanza et al., 2012; Astell-Burt et al., 2013). Several studies have demonstrated that physical activity completed in greenspace is associated with increased physical and psychological benefits in comparison to physical activity carried out in other settings (Duncan et al., 2014; Mitchell, 2013;

Pretty et al., 2005; Richardson et al., 2013; Thompson Coon et al., 2011). Interestingly, an important precondition for the use of greenspace for physical activity is the perception of safety pertaining to the greenspace (Jansson et al., 2013). This is especially true for youth, wherein parental perceptions of safety influenced the likelihood of youth engaging with greenspace (Ferdinand et al., 2012). Moreover, social cohesion (defined as the shared norms and values, existence of positive relationships, and feelings of being accepted and belonging) within a neighborhood also plays an important role in mediating the associations between greenspace exposure and mental health (Jennings & Bamkole, 2019). To illustrate, gardens can provide a space for individuals to connect with others (‘Yotti’Kingsley & Townsend, 2006) and parks may support participation in physical activity (Messiah et al., 2018), which may promote interest in engaging with greenspace (Seaman et al., 2010).

Other Potential Pathway

The biodiversity hypothesis suggests that interacting with organisms in natural settings enriches the human microbiome, aids immune regulation, and guards against inflammatory and immune-related diseases (Von Hertzen et al., 2011). Consequently, micro biodiversity could potentially be another pathway through which greenspace exposure positively impacts human health. The human microbiota which encompasses bacteria in the gut, mouth, and skin, significantly influences human health by participating in digestive, metabolic, and immune functions (Clarke et al., 2010). Various factors including age, ethnicity, and environmental exposures, like greenspace, impact the composition of the human microbiota (Dimitriu et al., 2019; Von Hertzen et al., 2011). In an analysis including data from 34 countries, it was found that increasing levels of residential greenness was associated with greater microbial richness in human skin and gut samples (Zhang et al., 2023). Butyrate (an important fatty acid in the human

microbiome) has been associated with mental health benefits via its involvement with the nervous, immune, and endocrine systems (Brame et al., 2021; Foster et al., 2017). To illustrate, in a sample of 54 mice, it was found that those exposed to higher quantities of soil butyrate (derived from plants) demonstrated reduced anxious behaviors in comparison to mice exposed to lower levels of or no levels of butyrate (Liddicoat et al., 2020). Taken together, the potential of greenspace to bolster the diversity of the human microbiome offers an interesting avenue that could positively impact mental health.

2.9 Dissertation Aims

Indeed, the potential benefits of greenspace exposure on mental health appears promising as evidenced above. However, there are notable areas in which our understanding of the associations between greenspace and mental health is limited. First, the majority of the studies included in reviews have been predominantly cross-sectional which limits our ability to understand the long-lasting influence of greenspace exposure in contributing to less symptoms of mental health problems (Van den Berg et al., 2015; Ye et al., 2022). Second, to the best of our knowledge, there has not yet been a systematic review that has evaluated the associations (if any) between greenspace exposure and suicide mortality, self-harm, and suicidal ideation, which remains a public health priority. Third, it has been demonstrated that socioeconomically deprived individuals disproportionately benefit from increased greenspace exposure (Balseviciene et al., 2014; De Vries et al., 2016) but also tend to reside in neighborhoods with less access to and quantity of greenspace (De Vries et al., 2020; Landry & Chakraborty, 2009), bringing forth important environmental inequities in the distribution of greenspace that could ultimately impact mental health. Consequently, further investigations on the role of socioeconomic status and greenspace distribution are warranted. Fourth, there is emerging evidence (Bolte et al., 2019;

Núñez et al., 2022) that the benefits of greenspace exposure are more salient depending on the sex/gender of an individual, although the findings remain mixed.

Therefore, the published studies included in this dissertation sought to determine whether greenspace exposure is associated with suicidal risk (i.e., suicide mortality, self-harm, and suicidal ideation) across the lifespan (**Chapter 3,** *published in Science of the Total Environment, Impact Factor: 10.75*) and to better understand the associations of greenspace exposure with internalizing and externalizing mental health problem symptoms across childhood and adolescence in a population-based sample of Canadian youth (**Chapter 4,** *published in Social Psychiatry and Psychiatric Epidemiology, Impact Factor: 4.52*). Specifically, there were two research questions driving this doctoral research: (1) Is greenspace exposure associated with suicidal risk in youth and adults? (2) Is childhood residential greenspace exposure associated with internalizing and externalizing mental health problem symptoms in adolescence, while considering important individual, family, and neighborhood characteristics? Additionally, do such associations vary by sex and socioeconomic status?

Chapter 3: Association between greenspace exposure and suicide-related outcomes across the lifespan: A systematic review

Bolanis, D., Vergunst, F., Mavoa, S., Schmelefske, E., Khoury, B., Turecki, G., Orri, M., & Geoffroy, M. C. (2023). Association between greenspace exposure and suicide-related outcomes across the lifespan: A systematic review. *Science of the total environment*, 167451. https://doi.org/10.1016/j.scitotenv.2023.167451

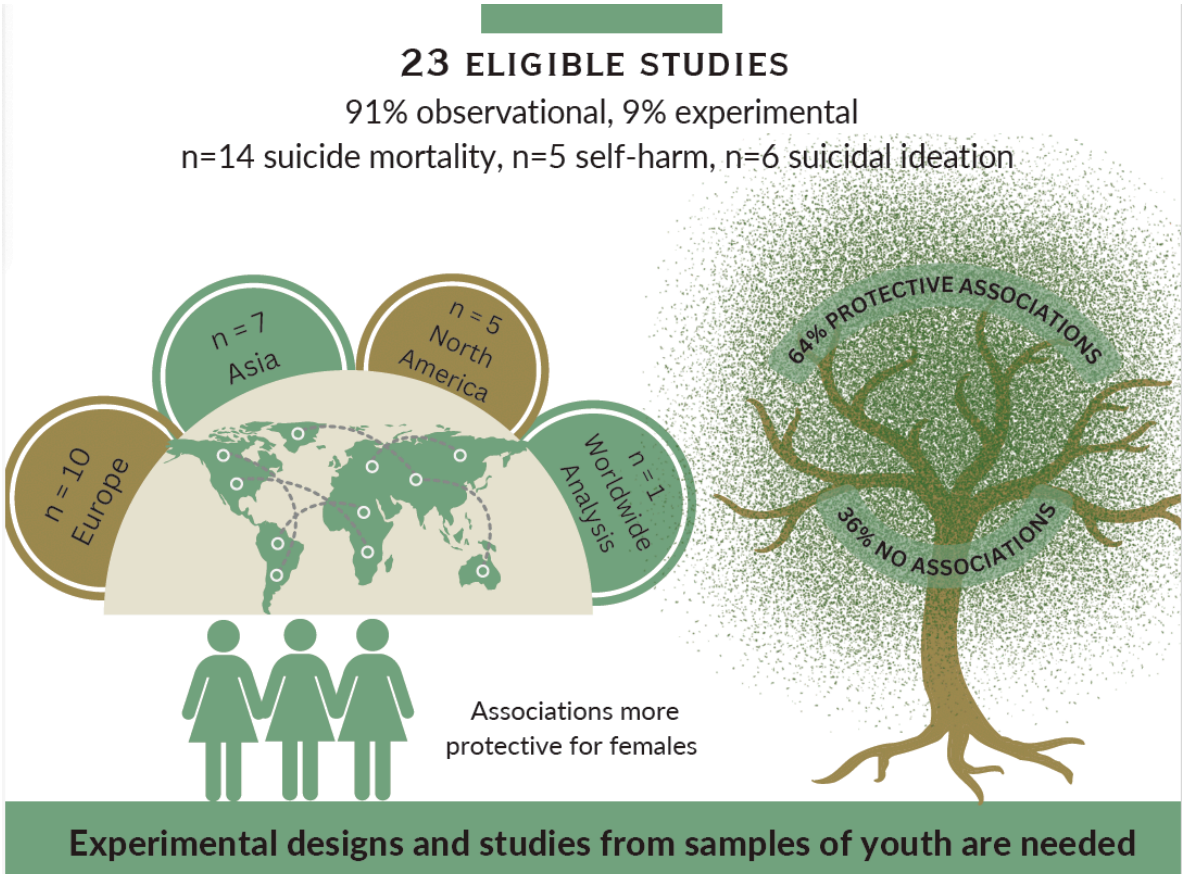
Conflict of Interest: The authors have no conflicts of interest.

Funding: Mrs. Bolanis is funded by the Canada Graduate Scholarships Doctoral (CGS-D) Program for the Social Sciences and Humanities Research Council (SSHRC). Drs Geoffroy and Turecki each hold a Canada Research Chair. This study was conducted using funding from the SSHRC (Dr. Geoffroy) and from the Research team in suicide prevention - Fonds de Recherche du Québec – Société et Culture – Papageno (Drs Geoffroy and Orri).

Highlights

- There is growing interest in the association of greenspace exposure and suicide-related outcomes, including suicide mortality, self-harm, and suicidal ideation.
- Our findings suggest a protective association between greenspace exposure and all suicide-related outcomes.
- The protective associations were stronger for women than for men.

Graphical Abstract



Abstract

A growing number of studies has linked greenspace exposure to suicide, but findings are inconsistent. We conducted a systematic review on the associations between greenspace exposure and suicide-related outcomes (namely, suicide mortality, self-harm, and suicidal ideation) up until January 6, 2023. We used the Mixed Methods Appraisal Tool (or MMAT) to assess the quality of the included studies.

In total, 23 studies met our inclusion criteria, consisting of 14 ecological, four cross-sectional, three longitudinal, and two experimental studies. Most studies were published in 2022 and conducted in Europe (*n*=10), Asia (*n*=7), and North America (*n*=5), with one worldwide analysis. Various indicators were used to assess greenspace exposure including objective measures (e.g., level of surrounding greenness, quantity, structural features, tree canopy coverage), and greenspace use (e.g., duration and frequency). Suicide mortality was the most studied outcome (*n*=14). Quality assessment showed that most (87%) of the included observational studies used representative samples. Protective associations of exposure to greenspace were reported for suicide mortality (9/14 or 64%), self-harm (*n*=3/5 or 60%) and suicidal ideation (*n*=4/6 or 67%), with nine or 36% studies reporting no association. Most of the included studies adjusted for key covariates such as age, sex, and socioeconomic status at various aggregate levels (e.g., household, city). For greenspace exposure and suicide mortality, studies stratified by sex (*n*=10) showed larger protective associations for females (*n*=7) than for males (*n*=4). However, the included studies showed high heterogeneity in terms of exposure indicators and greenspace definitions. Experimental studies and studies using youth samples were rare. While more research is warranted, preliminary findings suggest protective associations between greenspace exposure and suicide-related outcomes.

Introduction

There is growing recognition that individuals' mental health can be influenced by their physical and natural environments. For instance, factors such as increased weather temperature [1], air pollutants (e.g., particulate matter) [2], and urbanization [3] have been shown to contribute to poorer mental health. There is currently a surge of interest in studying the role of greenspace exposure, which refers to the availability or contact with natural or semi-natural outdoor areas completely or partially covered by vegetation (e.g., woodlands, parks, and forests [4, 5]). Several systematic reviews have evaluated the associations between greenspace exposure and a range of mental health issues [6-15], including a recent meta-analysis consisting of 18 cross-sectional and longitudinal studies evaluating depression and anxiety [16]. However, the quality of these studies varies considerably, with most studies employing cross-sectional designs.

Some prospective studies drawing from large samples have demonstrated protective associations between greenspace exposure and various psychiatric disorders. To illustrate, in a large representative sample of adults residing in cities across the United Kingdom, an interquartile increase in residential greenspace was associated with 4.0% lower odds of major depressive disorder, after adjusting for a range of confounding factors such as household and neighborhood socioeconomic status [17]. Similarly, it was found that for youth living in urban neighborhoods in Denmark, those exposed to the lowest level of greenspace had up to 55% higher risk of suffering from mental illness in adulthood (e.g. schizophrenia, substance abuse, and mood disorders), independent of family history of mental illness and other key confounding factors [18]. The protective role of greenspace exposure on mental health has been hypothesized to occur given that greenspace (1) reduces stress and increases attentional capacities, (2) mitigates exposure to harmful pollutants, and (3) strengthens psychosocial adaptation by

encouraging physical activity and social connection [19-21]. Given the well-known association between mental health and suicide [22, 23], it is reasonable to expect that greenspace exposure could play a similar beneficial role in mitigating suicidal risk.

Studies based on adults of varying age ranges linking greenspace exposure with suicide related outcomes have produced mixed findings. While some report lower rates of suicide mortality in regions with increased levels of residential greenspace [24, 25], others have found no associations [26, 27]. Additionally, the association between greenspace exposure and health may vary between sexes, with some evidence suggesting that greenspace has greater benefits for females' physical health [28] and cognitive function [29] than for males. For suicide-related outcomes, sex differences in greenspace associations with suicide-related outcomes have yet to be clarified as findings have been inconsistent [27, 30].

Suicide is one of the leading causes of death worldwide [31, 32], accounting for 1.4% of all deaths globally [33]. There is an urgent need to better understand the role of modifiable environmental factors, such as greenspace exposure, which could be a source of influence [34]. Therefore, the findings from this review will provide valuable insights for decision-makers, inform future research, guide the planning and design of greenspace, and contribute to the development of effective suicide prevention strategies. The aim of this study was to systematically review existing evidence on the association between greenspace exposure and suicide-related outcomes across the spectrum, i.e. suicide mortality, self-harm, and suicidal ideation. Additionally, we aimed to provide sex-specific differences in outcomes when data was available.

Method

This systematic review was conducted in accordance with the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) 2020 guidelines [35]. The review protocol was registered in PROSPERO (CRD42021229744).

Eligibility Criteria

Articles were included if they: (1) reported the associations of outdoor greenspace with suicide mortality, self-harm, or suicidal ideation; (2) were published in peer-reviewed journals in either French or English; (3) included original data; (4) used either subjective or objective measure(s) of greenspace. Studies that focused on blue space, or indoor vegetation (e.g., house plants), pictorial representations of greenspace (e.g., images or videos) or sensory aspects of greenery (e.g., sound, audio clips, or smells), or used qualitative methods, were excluded.

Information Source and Search Strategy

One of the authors (DB) conducted a comprehensive search on the OVID platform, including PyscInfo, MEDLINE, and Web of Science, to identify published articles (from inception up to January 6, 2023) that examined the associations between greenspace exposure and suicide mortality, self-harm, and suicidal ideation. Additionally, the reference lists of all included studies were manually searched to identify additional relevant studies that may not have been captured by the search algorithm.

The search strategy combined terms related to greenspace (e.g., greenery, garden, park, natural environment) and suicide-related outcomes (e.g., suicide mortality, suicide attempt, self-harm, suicidal ideation, non-serious suicidal self-injury). The initial search was developed in collaboration with an expert librarian (EK) specifically for PsycInfo (Ovid), and it was subsequently adapted for the other databases. The search was further updated in collaboration

with an expert librarian (JB). A complete list of search terms used for all databases can be found in **Appendix Tables A1-A3**.

Selection Process

After removing duplicates, three researchers (DB, ES, LA) independently reviewed the title and abstracts of all articles to assess their suitability for inclusion using a blinded standardized protocol that incorporated a set of eligibility criteria derived from best practice guidelines for abstract screening in large-evidence systematic reviews and meta-analyses [36]. Subsequently, the researchers (DB, ES, LA) independently and blindly reviewed the full-text articles that remained after the abstract screening process to determine their eligibility for inclusion (agreement on inclusion, *kappa coefficient*=0.99). Disagreements between researchers were resolved through discussion, and, if necessary, through consultation with a fourth author (M-CG).

Data Collection Process and Risk of Bias Assessment

The primary investigator (DB) developed a data extraction form on Microsoft Excel. The same researcher (DB) extracted the data, and three other researchers (M-CG, MO, FV) verified the accuracy of the data extraction. Any discrepancies were resolved through discussion. The following information was extracted from each eligible article: first author of the article, year of publication, study design, sample size, study population and setting (i.e., study location (country), age, sex/gender, ethnicity), greenspace definition, greenspace exposure metric, covariates, and fully adjusted results. If a study's main result(s) was not available in the main text or supplementary material, we contacted the corresponding author to obtain the information. We sent up to two follow-up emails to corresponding authors to request the information; if no response was received, we extracted data based on the available published information. In the

summary figure, we indicate whether the reported associations between greenspace and suicide-related outcomes are positive (i.e., protective when there is at least one positive association across greenspace indicators), negative (i.e., harmful when there is at least one negative association across greenspace indicators) or null (i.e., non-significant). Considering the wide range of greenspace exposure indicators and buffer sizes, coupled with data collected at both ecological and individual levels, meta-analysis was not suitable, and therefore, results are described narratively.

We categorized greenspace measures as objective and subjective based on the existing literature [8, 37]. *Objective greenspace* measures evaluate the proximity (e.g., distance to greenspace), quantity (e.g., total amount of greenspace within a given area), and visibility (e.g., view of greenspace from specific location or area) of greenspaces that are available and that individuals may come into contact with [38-40]. Common metrics used include the Normalized Difference Vegetation Index (NDVI) and percentage of green cover, which are generally extracted from satellite remote sensing images, land cover map, and Google Street view [4, 41]. *Subjective greenspace* measures aim to describe people's experiences of greenspace such as evaluating the quality (e.g., micro features or characteristics) of greenspace or quantifying visits/activities (e.g., duration and frequency) carried out in greenspace [20, 42]. Experimental designs have been used to evaluate the effect of prescribed activities in greenspace (e.g., walking, hiking, gardening) [15] to determine the causal influence of greenspace on mental health outcomes.

Following prior systematic reviews [14, 43], we used the Mixed Methods Appraisal Tool (MMAT) to appraise and describe included studies based on their design (e.g., randomized controlled trials and quantitative non-randomized trials such as observational, experimental, etc.)

[44, 45]. The MMAT includes five [44, 45] items tailored to each study design [46, 47]. The risk of bias for each study was scored as low ("yes" on MMAT, indicated higher quality), unclear ("can't tell" on MMAT, indicated uncertainty in quality), or high ("no" on MMAT, indicated lower quality) (see Fyfe-Johnson et al. [14]). One author (DB) completed the quality assessment for all included studies and three authors (M-CG, MO, FV) subsequently completed the MMAT independently. Any discrepancies were resolved through discussion.

Results

Study Selection and Overview of Studies

We initially identified 8,566 records through our database searches. After removing duplicates, we screened 6,079 records, of which 33 were reviewed as full-text articles, with 21 retained for review (PRISMA 2020 flow diagram, **Figure 1**) [24-27, 30, 48-63]. In addition, we conducted searches of the reference lists of the included studies and identified one additional article [64] and then identified one additional article by manual search [65]. A total of 23 articles were thus included in the final review (studies excluded during the full-texts screening process are listed in **Appendix Table A4**).

Characteristics of the retained studies including greenspace exposures, suicide-related outcomes, and main adjusted outcomes are presented in **Tables 1-3**. The year of publication of the studies ranged from 2008 (*n*=1) to 2023 (*n*=1), with the majority published in 2022 (*n*=8). Ten studies were conducted in Europe, while seven in Asia, five in North America, and one included data from 183 countries [58]. Most of the studies were observational (91%) while two (9%) had experimental designs. The observational studies consisted of both ecological (i.e., aggregated area-level data) (*n*=14), and individual-level data, including cross-sectional (*n*=4), and longitudinal cohort (*n*=3) designs. The statistical sample size varied greatly in observational

studies, ranging from 19 [56] to 296 [63] urban and/or rural areas in ecological studies, and 61 [55] to 8,741,021 [54] participants in studies using individual-level data. The number of participants included in experimental studies ranged from 15 [64] to 17 [53]. The populations evaluated in the studies included youth (*n*=1), adults, and the general population. An array of covariates was used across the 21 observational studies ranging from the individual to household to area levels (e.g., city). The most common adjustments at the individual level were for demographic characteristics, such as age, sex (or gender) and marital status. At the household level, the most common adjustment was for household income, while at the area level, adjustments were commonly made for air pollution, urbanicity, and socioeconomic status. An overview of the studies examining greenspace exposure and the direction of associations with suicide-related outcomes can be found in **Table 4**.

Ratings for each MMAT question can be found in **Appendix Table A5**, stratified by study design. Regarding the risk of bias assessment, 20 (87%) out of the 23 studies met the criteria for sample representativeness. In the majority of the observational studies (95%), the greenspace exposure metrics and suicide-related outcome measures were deemed appropriate. Fourteen out of the 21 (67%) observational studies administered the greenspace metric as intended (e.g., consideration of whether changes occurred in exposure status among participants).

Greenspace Metrics

Greenspace was defined as natural land (e.g., woodland, agricultural land, grassland, forests, grass/shrubs) surrounding a given area, such as residential home addresses, cities, schools [52], or prison establishments [49]. The majority of studies focused predominantly on urban regions, although one study included a mix of urban and rural regions [57].

Most studies used an objective measure of greenspace (87%), while the remaining 13% used subjective measures. The most commonly used objective indicators were the proportion of greenspace (i.e., green land cover) within various physical area classes, such as parks and municipalities, and the level of greenness assessed through the Normalized Difference Vegetation Index (NDVI) derived from satellite remote sensing data. Less commonly used greenspace indicators included the amount of tree canopy cover [61, 62, 65], structural features (e.g., mean green patch area/distance, patch density) [51, 62] and the perceived decrease of time spent in natural green settings [55]. In studies that used individual-level data, greenspace exposure was characterized within circular buffers around residential or school addresses (i.e., mean or max NDVI values) ranging from a radius of 100 m to 1000 m. Other studies using individual-level data defined greenspace exposure as the proportion of greenspace in physical areas averaging 4 km^2 [48] and as the number of parks and green areas per capita (maximum 33.1m^2/per capita) [25]. Studies using ecological-level data often relied on the proportion of greenspace within a given administrative area as a measure of greenspace exposure, which encompassed larger regions (e.g., 5000 m^2, Bixby et al. [27]) in comparison to smaller buffers evaluated in areas surrounding residential or school addresses. Moreover, the use of ecological-level greenspace indicators involved the evaluation of annual greenness levels, both at the country level [58] and within buffers (ranging from 100 m to 800 m) surrounding housing communities [59].

In experimental studies [53, 64], greenspace exposure was characterized by the frequency and duration of walks in forest settings. Specifically, the frequency of walks ranged from 1 to 3 times per week over a period of 9 to 13 weeks, with durations typically lasting 2 to 3 hours.

Suicide-Related Outcomes

Suicide mortality was examined as an outcome in 14 (61%) of the studies, self-harm in 5 (23%) studies, and suicidal ideation in 6 (26%) studies. All studies evaluating suicide mortality used record linkage to death certificates as defined by the International Statistical Classification of Diseases classification codes (ICD-10 X60-X84) or similar codes available in the study's country. Regarding self-harm, 3 (60%) studies used record linkage and 2 (40%) used a questionnaire-based assessment. Additionally, for studies evaluating suicidal ideation, 5 (83%) used a questionnaire and 1 (17%) constructed a suicidal ideation index via an online search engine in China. Further details regarding suicide-related outcomes of the included studies can be found in **Appendix Table A6**.

Suicide Mortality

Fourteen studies, including 10 ecological [24, 27, 51, 56-60, 62, 65], 3 longitudinal [26, 30, 54], and 1 cross-sectional [48] evaluated the associations between greenspace exposure and suicide mortality. Three of these studies reported the associations between greenspace exposure and suicide mortality by sex, with no results on the total sample provided [27, 54, 57]. Of these 3 studies, the direction of associations between greenspace exposure and suicide mortality were mixed; one study found that park density and woodland coverage was protective of suicide mortality [57], another found no significant associations [27], and one concluded that increasing levels of greenness increased suicide mortality or did not influence it, dependent on sex [54].

Five studies investigated the level of greenness using NDVI with marked inconsistency in the direction of the associations. Two studies found that increasing levels of greenness were associated with lower rates of suicide mortality at the country level [58] and at 300 m and 1000 m buffers surrounding residential addresses [30]. Conversely, no protective associations were observed between levels of greenness and suicide mortality surrounding urban public housing

communities across buffers of 100 m, 200 m, 400 m, and 800 m [59] or residential addresses in the Netherlands across buffers of 300 m, 600 m, or 1000 m [26].

Three studies found that for the general population in the Netherlands, Korea, and Taiwan, increased quantity of greenspace was associated with lower suicide mortality. For instance, municipalities [24] with large or moderate proportions of greenspace and counties with larger areas of greenspace [56] were associated with lowered suicide risk. Additionally, it was found that across 56 cities, increasing per capita park area was associated with a lower suicide mortality rate [60]. On the other hand, in studies using data from England with minimum mappable area of 5000 m^2 [27] and average physical area of 4 km^2 [48], the proportion of urban greenspace was not associated with suicide mortality.

Several studies evaluated various landscape metrics as they relate to greenspace, including structural features (e.g., green patch area) [51, 62] and percentage of tree canopy [65]. While increased tree canopy percentage, canopy shape, larger green patch area/mean patch area (i.e., average size of greenspace patches), and clumpiness (i.e., proportion of area covered by greenspace) were associated with lower suicide mortality [51, 62, 65], higher greenspace fragmentation (i.e., how scattered greenspace patches are) and density (i.e., number of greenspace patches in an area), longer green patch distance, and increased perimeter ratio (i.e., assessment of shape of greenspace) were associated with higher suicide mortality rates [51, 62, 65].

Self-Harm

Five studies, including 3 ecological [49, 50, 61] and 2 cross-sectional studies [25, 52], investigated the associations between greenspace exposure and self-harm. Three of them reported statistically significant associations between various greenspace metrics and self-harm.

For instance, Min et al. [25] found that residing in urban districts with less parks and greenspace per capita were associated with higher odds of suicide attempt, in comparison to districts with the most greenspace (OR=1.27, 95%CI [1.02-1.57]). Similarly, Lee et al. [61] found that for adults residing in Ohio, a one percentage point increase in tree canopy coverage at the Census Block level significantly lowered the suicide attempt rate by 0.9%, although residential surrounding tree canopy coverage was not associated with the suicide attempt rate. In another study, conducted in England and Wales, a higher proportion of greenspace within prison establishments was associated with lower incidents of self-harm [49]. Two studies found no association between greenspace and self-harm [50, 52]. In a sample of 5535 Canadian youth aged 11-20 years, an inter-quartile increase in levels of greenness surrounding schools within buffers of 500 m and 1000 m was not associated with suicide attempt [52]. Another study found that the percentage of urban greenspace was not associated with self-harm hospital admission rates in the United Kingdom [50].

Suicidal Ideation

Six studies, including 3 cross-sectional [25, 52, 55], 2 experimental [53, 64], and 1 ecological [63] investigated whether greenspace exposure was associated with suicidal ideation.

Of the 4 observational studies, 2 of them found statistically significant associations between greenspace and suicidal ideation while 2 did not. Two studies found that districts with greater parkland area in Korea and China were associated with lower odds of suicidal ideation [25, 63]. Moreover, a study of psychiatric inpatients (*n*=61) in Toronto, found that their perceived decrease of time spent in greenspace during the Covid-19 pandemic was associated with a trend in higher odds of experiencing suicidal ideation, although confidence intervals included one (Odds Ratio=4.71, 95%CI [0.78-28.34]) [55]. Srugo et al. [52] found that in a sample of youth

aged 11-20 years, increasing levels of greenness surrounding the school environment was not associated with suicidal ideation in buffers of 500 m and 1000 m.

The two experimental studies that evaluated the frequency and duration spent in greenspace in reducing the severity of suicidal ideation for psychiatric inpatients found mixed evidence. In Iwata et al. [64] pre-post design, 15 patients (mean age=47 years) reported a reduction of suicidal ideation, according to the Beck Depression Inventory and the Hamilton Depression Rating Scale, after receiving a 13 week intervention consisting of 2-hours of activities in various forest settings (i.e., 1-1.5-hour forest walks followed by 30-minutes of socializing). In comparison to their baseline suicidal ideation scores patients reported lower scores post intervention (means presented in study's figures only). Using a randomized cross-over design, Sturm et al. [53] evaluated the effects of hiking on 17 adults (mean age=43 years) at elevated risk for suicide who enrolled in a 9-week mountain hiking program (3 hikes per week, 2-3 hours each) versus a 9-week control period in which they received their typical treatment (e.g., psychotherapy). At baseline and follow-up, suicidal ideation was measured using the Beck Scale of Suicidal Ideation. Similar to Iwata et al. [64], the severity of suicidal ideation decreased from baseline (Mean score=10) to follow-up (Mean score=6) during the hiking phase (Cohen's d= -0.79, $p<0.005$). However, the severity of suicidal ideation also decreased, but to a lower extent, during the control phase from mean scores of 10 to 8 (Cohen's d= -1.8, p=0.212). Across both the hiking and control conditions, the reduction in severity of suicidal ideation was not significant (Cohen's d=0.29, p=0.25), suggesting that it is not possible to ascertain whether mountain hiking ameliorates suicidal ideation more than traditional treatment options.

Associations by Sex

Of the 23 included studies, 10 presented associations between greenspace exposure and suicide mortality stratified by sex [26, 27, 30, 51, 54, 56-58, 60, 62] (**Table 5**).

Of these 10 studies, 4 evaluated the level of greenness via NDVI and found mixed results. Asri et al.[58] identified that the increasing annual average value of greenness (surrounding buffer size not provided) across 183 countries was associated with lower suicide mortality for females and males, of similar magnitude. On the other hand, Helbich et al. [26] did not find significant associations that increasing levels of residential greenness at surrounding buffers of 300 m, 600 m, or 1000 m was protective for either females or males. One study in Belgium found that at surrounding buffers of 300 m and 1000 m increasing levels of residential mean greenness was associated with lower suicide mortality for females, but not males [30]. Lastly, although living in neighborhoods in the Netherlands with higher levels of mean greenness (surrounding buffer size not provided) did not influence the suicide mortality rate in males, it was found that this would actually increase the suicide mortality rate in females [54].

Four studies evaluated whether the quantity of greenspace influenced suicide mortality differently for females and males. Although one study found that the greenest (versus least green) urban areas were not associated with suicide mortality for both females and males [27], another study demonstrated that increasing green coverage was associated with lower suicide mortality with similar estimates for females and males [56]. In contrast, Kim and Sung [60] found that for females (but not males), increasing park area was associated with a lower suicide mortality rate. A Japanese study found that associations with suicide mortality varied depending on participant sex, age, and city size [57]. For instance, in large cities, increasing park density for females (aged 18-39 years) and males (aged 18-39 and 65+ years) was associated with lower suicide mortality. Conversely, in small/medium cities, park coverage was associated with lower suicide mortality in

females (aged 40-64 and 65+ years), while in rural areas, woodland coverage was associated with lower suicide mortality in males only (age 40-64 and 65+ years).

Furthermore, in studies examining various landscape features of greenspace, differing metrics were associated with different suicide mortality rates depending on sex. For example, Shen and Lung [51] found that larger green patch area was associated with a lower suicide mortality rate in females, while higher greenspace fragmentation and longer green patch distance increased it. In males, however, only higher greenspace fragmentation was associated with a higher suicide mortality rate. Similarly, another study demonstrated that some metrics were associated with higher (e.g., patch density and perimeter area ratio) or lower (e.g., percentage of landscape, mean patch area) suicide mortality for females; however, for males, only an increase in patch density was associated with higher suicide mortality rates (null results for all other greenspace metrics) [62]. Additionally, it was found that, for both females and males, increased tree canopy was associated with lower suicide mortality rates, while increased perimeter ratio was associated with higher suicide mortality rates.

Discussion

To our knowledge, this review represents the first comprehensive examination of the published evidence on the associations between greenspace exposure and suicide outcomes, including suicide mortality, self-harm, and suicidal ideation. The search of three databases identified 23 eligible studies, mostly observational, with a focus on suicide mortality and took into account confounding factors such as age, sex, and socioeconomic status at household and area levels. The overall findings suggest that exposure to greenspace is associated with lower suicide-related outcomes, with 64% of associations showing a positive association, particularly

among females. However, uncertainty persists, as 36% of associations did not report such associations.

Interpretation of Findings

For suicide mortality, 9 out of the 14 studies reported a protective association with greenspace exposure. These estimates are consistent with findings from studies of greenspace exposure and other psychiatric diagnoses [17, 18] including a recent meta-analysis consisting of 18 studies which found that both increasing proportions (merged Odds Ratio= 0.96, 95%CI [0.95, 0.98]) and levels (merged Odds Ratio= 0.93, 95%CI [0.89, 0.98]) of greenspace were associated with a lowered risk of depression [16]. Additionally, the results align with findings from 4, 645, 581 adults in the United Kingdom which demonstrated that small parks (i.e., areas for rest and recreation <4000 m^2) were protective of all-cause mortality, although suicide mortality was not investigated [66]. However, 3 out of the 14 studies did not find that greenspace exposure was protective of suicide mortality across the full sample [26, 48, 59], while 2 studies only reported associations by sex and found that greenspace exposure was either not protective [27, 54], harmful [54], or depended on the participant's sex. Although it is not possible to ascertain the differences of observed associations in these studies, some methodological variations should be noted. These include lack of adjustment for key variables at the individual level, including previous mental health history [54] and socioeconomic status [59], as well as differing metrics used for greenspace exposure, such as the use of different buffer sizes [26, 59], and area coverage [27, 48]. Regarding the associations with suicide mortality within specific buffer sizes, the findings from this review did not yield consistent results given that not all studies reported the buffer sizes investigated nor did they evaluate the same surrounding buffer sizes. For instance, across buffers of 300 m and 1000 m, increasing levels of greenness was not

associated with suicide mortality in one study [26], although in another study [30], increasing levels of greenness at surrounding buffers of 300 m and 1000 m was associated with lower suicide mortality. Alternatively, in surrounding buffers of 100 m, 200 m, 400 m, and 800 m, increasing levels of greenness was not associated with suicide mortality [59]. Previous work has highlighted that small buffer sizes (i.e., <100 m) are representative of vegetation directly outside the area of residence, whereas medium buffer sizes (i.e., >100m) represent vegetation that is visible around the home; and such differences in buffer distance have been hypothesized to contribute to the mechanisms by which greenspace benefits mental health [21, 67].

A recent systematic review on physical health outcomes suggested that greenspace exposure was more beneficial for females than for males [28]. These results parallel findings from the current review illustrating that greenspace exposure was more protective against suicide mortality for females compared to males. Although the mechanisms by which sex modifies the associations between greenspace and mental health remain unknown, it was hypothesized that physiological and psychological responses to greenness may differ across female and male individuals [28, 68]. Furthermore, more research is needed to better understand whether these associations are sustained across the full spectrum of suicide-related outcomes, i.e., self-harm and suicidal ideation. Additionally, the associations by sex might also depend on the specific indicator used to measure greenspace exposure. For example, Vaz et al. [62] found that aspects of the urban environment such as percentage of green landscape and mean patch area were associated with lower suicide mortality in females, while Shen and Lung [51] found that higher greenspace fragmentation was associated with more suicide mortality in males. These findings are in line the greenspace literature more generally, as various studies have highlighted that

associations with health and mental health also vary depending on the greenspace indicator used [69-71]. Further work is needed to address these unresolved questions.

Although greenspace exposure is associated with reduced suicide mortality in many studies, it is not possible to ascertain the temporal sequence from initial exposures to death by suicide as a function of greenspace exposure. Suicidal risk is complex comprising of an interplay between proximal (e.g., mental illness) and distal (e.g., environmental influences) factors that vary greatly among individuals [72, 73], and the predominance of ecological designs that evaluated suicide mortality limit the ability to understand individual heterogeneity.

Regarding suicidal behaviors (i.e., self-harm and suicidal ideation), 6 out of the 9 studies found protective associations. These studies employed a variety of objective indicators (e.g., level of surrounding greenness) and subjective indicators (e.g., perceived decreased time spent in greenspace) of greenspace exposure. Notably, 2 out of the 9 studies did not find that greenspace exposure was protective against suicidal behaviors [50, 52], while 1 demonstrated a trending association [55]. Of these 3 studies, 1 evaluated the associations of school surrounding greenness and suicidal behaviors in youth, suggesting that greenery in schools may not have an important influence on suicidal risk [52]. As for studies that evaluated prescribed walking programs in green settings [53, 64], it is unclear whether the observed decrease in suicidal ideation scores were due to walking in the green setting or mediated via physical activity. A recent meta-analysis of randomized controlled trials and non-randomized studies (n=15) demonstrated that prescriptions from a mental health professional to spend time in green environments (e.g., by walking, gardening, engaging in mindfulness and relaxation) had a moderate effect on depression scores [74]. Similarly, a recent randomized controlled trial including 37 outpatients diagnosed with major depressive disorder found that a 60-minute walk in green and urban settings reduced

negative affect, although larger effects were observed for participants who walked in the green versus urban setting [75]. These findings underscore the importance of randomized controlled studies to help clarify whether greenspace exposure can causally decrease the risk of suicidal ideation and self-harm. Such interventions hold promise as complementary prevention strategies that are widely accessible and free of charge [34].

In our analyses, we reported fully adjusted estimates as there is evidence suggesting that conditions of the natural environment are closely associated with various factors that can contribute to suicide [76, 77]. For instance, healthier individuals may select residential locations with more green areas, increasing opportunities for exercise and lowering exposure to air pollutants [78]. It is also possible that those with severe mental illness reside in disadvantaged neighborhoods given socioeconomic disparities [79]. It has been documented that disadvantaged areas are more likely to have less greenspace [80-82], which brings forth important equity concerns. Most of the included studies in this review controlled for these factors, and adjustment for socioeconomic indicators at the household (e.g., income, employment status) or area (e.g., deprivation indices) level was generally adequately considered. However, we recommend that future research also control for familial mental health history in analyses, as adjustment for these variables can provide a better understanding of the temporal sequence of associations between greenspace exposure and suicide.

The mechanisms in which greenspace promotes good mental health are not fully understood. It has been hypothesized that greenspace offers health benefits through three prominent pathways: (1) reducing stress and restoring attention, (2) increasing physical activity and social cohesion, and (3) mitigating exposure to environmental hazards such as heat, noise, and air pollution [19-21]. However, the extent to which these proposed pathways apply to

suicide-related outcomes remains unclear, especially because pathways may depend on the health outcome in question [83]. For instance, both the stress reduction [84] and attention restoration [85] theories posit that greenspace exposure helps individuals cope with stressful life events and emotional pain, which, in turn, reduces stress [20], and thus the likelihood of developing suicidal behaviors. Alternatively, there may be a link between distal risk factors (e.g., greenspace exposure) and proximal risk factors (e.g., mental health), emphasizing the importance of addressing both environmental factors (e.g., urban planning) and psychosocial components associated with suicide [72]. In practice, both proximal and distal pathways may pay a role, depending on individual and contextual factors. Future studies should explore which pathways are more dominant in the relationship between greenspace exposure and suicide-related outcomes.

Limitations and Future Research Directions

Several limitations need to be considered when interpreting the findings of the current review. First, the heterogeneity in greenspace definitions and indicators used across studies precluded meta-analysis or the aggregation of data at various levels (i.e., area versus individual levels). Given the increasing number of studies in this field, more standardized procedures are needed to support meta-analytic methods in relation to greenspace exposure and mental health studies [83, 86]. All of the included observational studies relied on greenspace assessment measures calculated for geographic areas which introduces the modifiable areal unit problem (MAUP) [87]. The MAUP is where the choice of the size of geographical area under study and/or the boundary chosen to represent a given area, can alter associations between greenspace exposure and outcomes [88, 89]. Aggregating data at the area-level introduces the ecological fallacy bias, in which patterns observed at the area-level may not reflect associations at the

individual-level [90]. Additionally, many of the included studies characterized the greenspace exposure metric across diverse buffers ranging in size (i.e., 100 m to 1000 m) and it is important for future research to clarify which surrounding buffer sizes would be most appropriate to study and how these buffer sizes translate to possible mechanisms and pathways.

Second, all but one of the included studies were drawn solely from high income regions including Europe, North America, and Asia. Asri et al. [58] completed a global analysis including high-, middle-, and low-income regions and found that country level of greenness significantly decreased the suicide mortality rate in low-income regions. However, low- and middle-income regions remain largely underrepresented in the literature and the development of greenspace remains a challenge in these regions [91]. Future studies should also explore other geographic landscapes which may be more salient in low- and middle-income regions, such as blue spaces [92] and arid climates [93].

Third, only one of the studies in the review evaluated the role of rural greenspace (as opposed to urban greenspace) and found that rural greenspace was protective of suicide mortality in males but not in females [57]. Future studies are needed to elucidate the associations between rural greenspace exposure and suicide-related outcomes given that discrepancies exist between urban and rural areas, such as socioeconomic disparities, inequitable access to health care services [94, 95], differences in population density, and exposure to air pollutants [96, 97]; all of which are important determinants of mental health and suicide [98].

Fourth, most of the evidence included in this review was derived from observational studies, and therefore, we cannot rule out unmeasured confounding factors that may be driving the observed associations. Only one randomized cross-over trial was found in this review [53], and it was difficult to determine the extent to which mountain hiking was beneficial in reducing

suicidal ideation, given that suicidal ideation scores also improved during the control phase (i.e., psychotherapy and pharmacological treatment). Robust randomized controlled studies are still needed to clarify the causal effect between greenspace exposure and suicide-related outcomes. We encourage future studies to explore the relationship between greenspace interventions and severe mental illness, as greenspace-based interventions present an opportunity to promote mental health [99].

Fifth, only one of the included studies evaluated the associations between greenspace exposure and suicidal ideation and self-harm in youth. There is a growing body of evidence that highlights the protective role of greenspace exposure on youth's mental health [7, 14]. Future studies are needed to clarify whether greenspace exposure protects against suicide-related outcomes in young people, particularly given recent trends in emergency department visits for suicidal ideation and suicide attempts in this population [100].

Conclusion

In this systematic review, over two-thirds of the included studies were published within the past 5 years, indicating a rapidly growing interest in the field of greenspace exposure and mental health. The accumulated evidence suggests that greenspace exposure may have a protective role across the entire spectrum of suicide outcomes, including suicide mortality, self-harm, and suicidal ideation, with larger putative benefits observed among females. However, evidence remains weak, given the high heterogeneity in study designs and methodologies used. Further studies are therefore necessary. In particular, experimental designs are needed to determine whether greenspace interventions as a complement to traditional treatment options, such as psychotherapy and pharmacotherapy, may be effective in mitigating the risk of non-fatal suicidal behaviors. Already, a growing body of literature supports the effectiveness of greenspace

prescriptions to improve outcomes for physical health and serious mental illness [74]. Recognizing the significance of greenspace exposure in suicide prevention can contribute to the development of policies that promote access to and utilization of greenspace and thus improve mental health outcomes for whole populations.

Acknowledgements

The authors would like to acknowledge the important contributions of Emily Kingsland (liaison librarian) and Jill Boruff (associate librarian) at McGill University, for their invaluable assistance in crafting precise search terms for our systematic review. Their expertise played a pivotal role in enhancing the quality of our research. We are also thankful to Lauren Anzarouth, research assistant at McGill University, for diligently screening numerous articles, contributing to the thoroughness of our review process.

Tables & Figures

Figure 1. Flow diagram for study selection

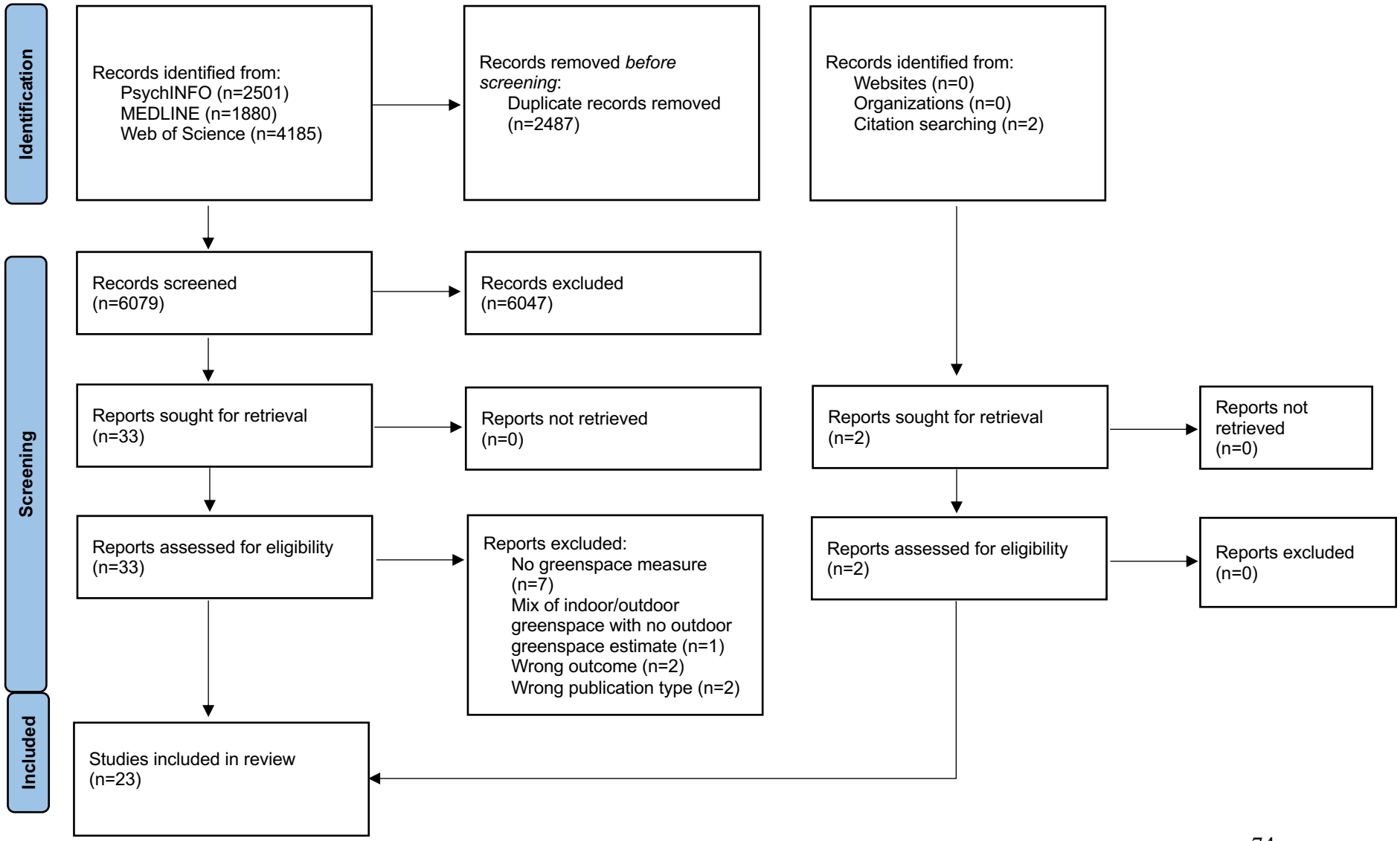


Table 1. Characteristics of included studies: greenspace and suicide mortality (*n*=14)

First author, year	Study design	Sample size	Study population and setting	Greenspace definition	Greenspace exposure metric	Covariates	Fully adjusted results
Level of greenness							
Asri et al., (2022)	Ecological	183 countries	Adults aged 15+ years worldwide; 49.9% female	Level of greenness at country level	NDVI data provided by the National Aeronautics and Space Administration with 1x1 km^2 spatial resolution were used to estimate level of greenness in each country. Monthly greenness estimates were calculated to capture the annual average values of greenness at the country level (i.e., based off of images for the months of January, April, July, October)	Population density, age, sex, burden of depressive disorders, healthcare expenditure, unemployment rate, divorce rate, economic status, educational attainment, urbanization, smoking prevalence, alcohol consumption, population without religion, temperature, PM2.5, and spatial–temporal autocorrelation	Increasing levels of greenness was associated with lower suicide mortality (RR=0.69, 95%CI[0.59,0.81])
Hagedoorn et al., (2022)	Cohort Longitudinal	8,741,021 adults	Adults aged 15-64 years in the Netherlands; 50% female; 81.4% Dutch	Neighborhood greenspace	Annual mean NDVI using 30 m resolution per neighborhood was retrieved from Landsat 5, Landsat 7, and Landsat 8 (obtained via Google Earth Engine)	Age, sex, nationality, marital status, household type, socioeconomic status, antidepressant prescriptions, moving status, moving frequency	Results for total sample are not reported, but stratified by sex. Neighbourhood greenspace was associated with elevated suicide mortality in females, but no association was found in males. See Supplement Table S7

Helbich et al., (2020)	Cohort Longitudinal	105,398 adults	Adults aged 15-64 years in Netherlands; 30.9% female	Green biomass (i.e., residential greenery)	Annual mean NDVI using 30 m by 30 m resolution at buffers of 300 m, 600 m, and 1000 m centered on current and past home addresses	Age, gender, nationality, employment status, household income, marital status, urbanicity, air pollution, social fragmentation	Inter-quartile increments of NDVI in 300 m, 600 m, or 1000 m buffers did not lower the odds of suicide mortality for the total sample in the highest quartile of greenspace OR= 1.04, 95%CI [0.95-1.13]; OR= 1.03, 95%CI [0.94-1.13]; OR= 1.00, 95%CI [0.92-1.11], respectively
Jiang et al., (2021)	Ecological	151 public housing communities	Adults with a mean age of 47(7.5) years in Hong Kong; 0.52(0.018) female	Urban greenness within public housing communities	Amount of urban greenery was assessed at buffers of 100 m, 200 m, 400 m, and 800 m around each housing community and its surrounding neighborhood using NDVI and Google Street View (GSV) images. GSV images calculate the ratio of greenery pixels to total pixels in a GSV image	Median age, percentage of residents of different marital status, percentage of residents in different age groups, percentage of residents with different education levels, household income, employment rates	Urban greenery at 100 m (β= 0.014, SE= 0.103, p= 0.894, p<0.01), 200 m (β= 0.003, SE=0.108, p= 0.981), 400 m (β= 0.119, SE= 1.14, p=0.297), and 800 m (β= 0.152, SE=0.105, p= 0.151) buffers around housing communities was not associated with suicide mortality
Mendoza et al., (2022)	Cohort Longitudinal	3,549,514 adults	Adults with a mean age of 46.9(17.8) in Belgium; 51.90% female	Urban residential greenness	NDVI data were obtained from Landstat-5 satellite images with a 30 m resolution and linked with residential addresses from Census data. Mean NDVI was assessed at buffers of 300 m and 1000 m within the residential addresses	Sex, age, living arrangement, individual socio-economic position, neighbourhood socio-economic position, migrant background	At buffers of 300 m and 1000 m, residential greenness was associated with lower suicide mortality: HR=0.93, 95%CI[0.89,0.97]; HR=0.94, 95%CI[0.90-0.98], respectively
Quantity of greenspace							

Bixby et al., (2015)	Ecological	5222 adults	Adults aged 15-64 years in England; 36.8% female	Urban greenspace including woodland, agricultural land, grassland and other natural vegetated land	Proportion of urban area covered by green land using Land Cover Map from remote sensing data (20 m-30 m pixels, minimum mappable area of 5000 m^2)	Age, income deprivation, air pollution	Results for total sample not reported. Overall, urban areas with more greenspace were not associated with suicide mortality for females and males. See Supplement Table S7
Helbich et al., (2018)	Ecological	16,105 adults	General population in the Netherlands	Municipality surrounding greenspace defined as agricultural and natural areas, and man-made greenery (e.g., parks)	Proportion (%) of greenspace per municipality using Geographical Information System (GIS) mapping with 25m x 25m spatial resolution	Sex, urbanicity, marital status, unemployment rate, housing values, availability of general practitioners, orthodox/protestant	Municipalities with a large (RR= 0.88, 95%CI [0.78-0.99] or moderate (RR=0.92, 95%CI [0.85-1.00]) proportion of greenspace were associated with lower suicide mortality compared to municipalities with less greenspace
Jiang, Stickley & Ueda, (2021)	Ecological	1741 municipalities	886,440 suicide deaths in general population in Japan between 1975-2014	Municipality surrounding greenspace defined as: (1) woodland (i.e., forest, grasslands, wildwoods) and (2) parks in urban and rural settings	(1) Woodland data was abstracted as area size within a municipality in a given year using Geographic Information Systems (GIS). (2) Park data was obtained using Python GeoPandas (version 0.8.0) wherein the geographic point was used to identify where each park was located in a given municipality. The proportion of park area size and density (i.e., number of parks per 1000 of the population) was	Population density, population in agriculture, population in industry, population in the service sector, fiscal strength, unemployment rate, marital status, psychiatric hospitalizations, fiscal strength, number foreign of residents	Results for total sample not reported. Overall, greenspace was associated with lower suicide mortality but associations varied based on sex, age, greenspace type, and area size. See Supplement Table S7

					evaluated in each municipality		
Kim et al., (2022)	Ecological	56 cities	General population in Korea; 0.5(0.01)[a]	Urban parks	Per capita park area (m^2/person) was obtained from statistical data available on the open data portal (stat. molit.go.kr/portal) of the Ministry of Land, Infrastructure, and Transport	Female population ratio, elderly ratio, per capita gross regional domestic product, basic living recipient ratio, divorce rate per thousand, number of beds per thousand	With every increase in 1 m^2 per person in park area, the suicide mortality rate per 100,000 people decreased by 0.46 (t= -2.57, p<0.05)
Mitchell & Popham (2008)	Cohort Cross-sectional	12,308 adults	Adults aged 16-45 years in England	Parks, other open spaces, and agricultural land, but excluding domestic gardens	Proportion of greenspace (quintile) in lower level super output areas (LSOA), used to report small area greenspace in England. LSOAs have a minimum population of 1000, a mean population of 1500, and an average physical area of 4 km^2	Age, sex, income deprivation, deprivation in education, skills and training, deprivation in living environment (including air pollution), population density, urban/rural classification	Increasing proportions of greenspace was not associated with suicide mortality (e.g., areas with most greenspace (5th quintile); IRR= 1.00, 95%CI [0.92-1.09] compared to the areas with the least greenspace (1st quintile))
Shen, Lung & Cui, (2022)	Ecological	19 counties	General population from Taiwan	Urban greenspace (i.e., woodland areas, forests and parks)	Green coverage (i.e., area of greenspace) collected and calculated from the database of the Ministry of the Interior and the Directorate General of Budget, Accounting, Statistics	N/A	Increasing green coverage was associated with lower suicide mortality (coef.= -0.21, 95%CI= [-0.28, 0.14]
Structural features of greenspace							

Shen & Lung (2018)	Ecological	48 administrative districts in Metropolitan region	General population from Tapei, Taiwan	Urban greenspace	Different landscape metrics (i.e., greenery structures) were evaluated using data from the National Land-Use Survey of the National Land Surveying and Mapping Center. (1) Greenspace fragmentation was measured as the total number of green patches over a certain area. (2) Mean green patch area was measured as an aggregate of the average area of each green patch and its area-weighted equivalent. (3) Green patch distance was measured as an aggregate of the average area between each green patch and its area-weighted equivalent	N/A	The total effect of green structures on the suicide mortality rate revealed that higher greenspace fragmentation (STEC= 0.13, $p<0.01$) and longer green patch distance (STEC= 0.35, $p<0.001$) increased the suicide mortality rate, while a larger green patch area (STEC= -0.42, $p<0.001$) would decrease the suicide mortality rate

Vaz et al., (2020)	Ecological	6457 adults	Adults aged 15-65+ years in Canada; 55% Female	Urban greenspace	Different landscape metrics pertaining to grass/shrub calculated using City Planning's Open Data Forest and Land Cover (2007) with land cover data set at a pixel size of 0.6m: (1) percent of landscape, (2) patch density, (3) mean patch area, (4) perimeter area ratio, (5) clumpiness of area, (6) percentage of like adjacencies, and (7) aggregation index were evaluated	N/A	An increase of the following landscape metrics was correlated with lower suicide mortality: grass/shrub percentage of landscape (β=-0.20, p< 0.01), grass/shrub mean patch area (β= -0.26, p< 0.001), grass/shrub clumpiness index (β= -0.20, p< 0.01) grass/shrub percentage of like adjacencies (β= -0.22, p< 0.01), and grass/shrub aggregation index (β= -0.22, p< 0.01). An increase in grass/shrub patch density (β= 0.23, p< 0.001) and grass/shrub perimeter area ratio (β= 0.24, p< 0.001) was correlated with more suicide mortality
Percentage tree canopy							
El-Mallakh et al., (2022)	Ecological	757,002 adults	General population from Kentucky, USA	Urban tree cover	Percentage of tree canopy per zip code using data from the US Geological Survey found online in the National Land Cover Database (NLCD) with pixels at 30 m^2	Annual income, ethnicity	Increasing tree canopy was associated with lower suicide mortality; rate=0.0091, SE=0.0026, 95%CI[0.0039,0.0142]

Vaz et al., (2020)	Ecological	6457 adults	Adults aged 15-65+ years in Canada; 55% Female	Urban greenspace	Different landscape metrics pertaining to tree canopy calculated using City Planning's Open Data Forest and Land Cover (2007) with land cover data set at a pixel size of 0.6m: (1) landscape shape index (i.e., measure of geometric complexity and disaggregation) and (2) perimeter area ratio (i.e., how patch perimeter increases per unit increase in patch area) were evaluated	N/A	Increased tree canopy landscape shape was correlated with less suicide mortality (β= -0.25, p<0.001). Increased perimeter area ratio was correlated with more suicide mortality (β= 0.38, p<0.01)

Note: NDVI= Normalized Vegetation Index. N/A= Nota available. RR= Relative Risk. CI= Confidence Interval. OR= Odds Ratio. IRR= Incidence Rate Ratio. STEC= Standardized Total Effect Coefficient. Coef.= coefficient. Mean age represented as mean (Standard Deviation)

[a]Population rate per 100,000 females expressed as mean (Standard Deviation)

Table 2. Characteristics of included studies: greenspace and suicide self-harm (*n*=5)

First author, year	Study design	Sample size	Study population and setting	Greenspace Definition	Greenspace Exposure Metric	Covariates	Fully adjusted results
Level of greenness							
Srugo et al., (2019)	Cohort cross-sectional	5535 youth	Youth aged 11-20 years in Canada; 56.8% female; 40.3% non-white	School greenness	Level of school greenness assessed via mean and max of the annual mean and maximum NDVI using 30 m resolution within 500 m and 1000 m from the centroid of the school's 6-digit postal code	Age, sex, self-reported socioeconomic status, ethno-racial background, season	Inter-quartile increments of mean or max NDVI in 500 m and 1000 m buffers was not associated with suicide attempt
Quantity of greenspace							
Min et al., (2017)	Cohort cross-sectional	196,894 suicide attempt	Adults aged 20-60+ years in Korea; 53.4% female	Exposure to parks and green areas per capita in cities and counties	Area-level codes were matched based on the number of parks and green areas in each district and were divided into quartiles (1st quartile= 14.90-22.40 m^2/capita; 4th quartile= 33.1 m^2/capita)	Age, gender, marital status, education, monthly income, job categories, physical activity, smoking, alcohol consumption, history of disease, Gross Domestic Product per capita	Districts with less parks and green areas per capita (1st quartile) were associated with higher odds of suicide attempt (OR=1.27, 95%CI [1.02-1.57]) in comparison to districts with the most parks and greenspace per capita (4th quartile)
Moran et al., (2020)	Ecological	103 prison establishments	Prisoners aged 18+ in England and Wales	Vegetative land cover within prison establishments (e.g., grass, bushes, trees)	Proportion of greenspace (%) within prison establishments using GIS mapping	Age, gender, marital status, education, monthly income, job categories, physical activity, smoking, alcohol consumption, history of disease, Gross Domestic Product per capita	In prisons with a higher percentage of greenspace, the incidence of self-harm was lower (β= -0.48, SE=0.17,p<0.01)

Polling et al., (2019)	Ecological	8327 hospital admissions	Individuals admitted aged 15+ in United Kingdom; 60.6% female; 44.8(16.0) non-white minority rate[a]	Urban greenspace	Percentage of greenspace in lower LSOA. Greenspace data sourced from an enhanced basemap based on Department of Communities and Local Government data (no further details reported)	Hospital of admission, deprivation, social fragmentation	Percentage of greenspace (least versus most quartile) was not associated with self-harm admission rates (SRR= 0.99, CrI [0.91-1.08])
Tree canopy cover							
Lee et al., (2023)	Ecological	275 census block groups	Adults aged 15-44 years in Ohio, USA; 0.51(0.01)[b] females; 0.52(0.02) non-white minority rate[a]	Urban tree cover	Proportion of tree canopy cover of each Census block was acquired from the Multi-Resolution Land Characteristics Consortium as a geospatial raster dataset with 30 m resolution. Additionally, residential tree canopy coverage was estimated using citywide parcel boundaries and land use information.	Foreclosed properties, vacancy rate, crime density, population density, area deprivation, non-white minority status, working age	A one percentage point increase in tree canopy coverage at the Census Block level significantly decreases the suicide attempt rate by 0.9% (coef= -0.901, SE= 0.329, p<0.01). A one percentage point increase in tree canopy coverage at the residential level was not associated with the suicide attempt rate (coef= -0.682, SE= 0.378, p>0.05)

Note: NDVI= Normalized Vegetation Index. CI= Confidence Interval. OR= Odds Ratio. SRR= Standardized Rate Ratio. CrI= 95% Credible Intervals. Coef.= Coefficient. SE= Standard Error. N/A= Not applicable.

[a]Non-white minority rate per 100,000 individuals expressed as mean (Standard Deviation)

[b]Population rate per 100,000 females expressed as mean (Standard Deviation)

Table 3. Characteristics of included studies: greenspace and suicide suicidal ideation (*n*=6)

First author, year	Study design	Sample size	Study population and setting	Greenspace definition	Greenspace exposure metric	Covariates	Fully adjusted results
Level of greenness							
Srugo et al., (2019)	Cohort Cross-sectional	5521 youth	Youth aged 11-20 years in Canada; 56.8% female; 40.3% non-white	School greenness	Level of school greenness assessed via mean and max of the annual mean and maximum NDVI using 30 m resolution within 500 m and 1000 m from the centroid of the school's 6-digit postal code	Age, sex, self-reported socioeconomic status, ethno-racial background, season	Inter-quartile increments of mean or maximum NDVI in 500 and 1000 m buffers was not associated with suicidal ideation
Quantity of greenspace							
Min et al., (2017)	Cohort Cross-sectional	218,729 adults	Adults aged 20-60+ in Korea; 53.4% female	Exposure to parks and green areas per capita in cities and counties	Area-level codes were matched based on the number of parks and green areas in each district and were divided into quartiles (1st quartile= 14.90-22.40 m^2/capita; 4th quartile= 33.1 m^2/capita)	Age, gender, marital status, education, monthly income, job categories, physical activity, smoking, alcohol consumption, history of disease, Gross Domestic Product per capita	Districts with less parks and green areas per capita (1st quartile) were associated with higher odds of suicidal ideation (OR=1.16, 95%CI [1.10-1.23]) in comparison to districts with the most parks and greenspace per capita (4th quartile)
Yao et al., (2022)	Ecological	296 cities	General population in China	City parkland (reflects the presence of greenspace for the whole city)	Proportion of parkland area (%) in a city calculated as the area of parkland to the total area of a city (km^2/km^2*100%). Data was derived from the Statistical Yearbook of Chinese Cities 2019	Population, gross domestic product per capita, unemployment rate, number of hospital beds, number of doctors, average annual temperature, average annual precipitation, environment stress	Residents residing in cities with the most greenspace (4th quartile) demonstrated lower suicidal ideation (Coef.= -0.057, SE= 0.020, p<0.01) in comparison to those residing in cities with the least greenspace (1st quartile)
Frequency and duration							

Holman et al., (2022)	Cross-sectional	61 adults	Adults aged 19-77 years (mean age- 38.4(13.5)) in Toronto from an inpatient psychiatric unit; 50.8% female; 41% non-white	Parks, gardens	Participants reported whether they had experienced decreased time spent in greenspace, categorized as yes or no	Age, gender	A perceived decrease in time spent outdoors was not associated with suicidal ideation and/or self-harm thoughts in patients who experienced a psychiatric hospitalization during the COVID-19 pandemic (OR=4.71; 95%CI [0.78-28.34])
Iwata et al., (2016)	Pre-post experimental	15 adults	Clinical sample of adults aged 32-72 years (mean age= 47 years) in Ireland; 80% female	Forest settings	The program consisted of activities in a forest setting for approximately 2 hours weekly, for 13 weeks. This included roughly 10 minutes of engaging in gentle warm-up exercises, 1–1.5 hours of forest walks, followed by approximately 30 minutes of refreshments/socializing in the forest sites	N/A	Results pictured in Figures 1 and 2 (of original publication) suggest that individuals who were enrolled in the 13-week forest walk program exhibited decreased suicidal ideation (assessed with both HRS and BDI) scores from pre-to post- program, although no formal statistical analyses are reported
Sturm et al., (2012)	Randomized controlled cross-over	17 adults	Clinical sample of adults with mean age 43.0(8.3) in Austria; 70% female	Mountain hiking	9-week program with 2-3h long mountain hikes, 3 times per week	N/A	During the cross-over phase of the study, there was no significant effect for suicidal ideation (p=0.25, d=0.29). Within the hiking phase of the study, suicidal ideation was significantly decreased (p=0.005, d= -0.79)

Note: NDVI= Normalized Vegetation Index. CI= Confidence Interval. OR= Odds Ratio. SRR= Standardized Rate Ratio. CrI= 95% Credible Intervals. Coef.= Coefficient. SE= Standard Error. N/A= Not applicable. d= Cohen's d. HDRS= Hamilton Depression Rating Scale. BDI= Beck Depression Inventory

Table 4. Direction of association between greenspace exposure and suicide-related outcomes (*n*=23)

Outcome	Greenspace	Adjusted Association
Suicide Mortality		
Arsi et al., (2023)	Level of greenness	+
Bixby et al., (2015)	Quantity	0
El-Mallakh et al., (2022)	Percentage tree canopy	+
Hagedoorn et al., (2022)	Level of greenness	− and 0[a]
Helbich et al., (2018)	Quantity	+
Helbich et al., (2020)	Level of greenness	0
Jiang et al., (2021)	Level of greenness	0
Jiang, Stickley & Ueda (2021)	Quantity	+
Kim et al., (2022)	Quantity	+
Mendoza et al., (2022)	Level of greenness	+
Mitchell & Popham (2008)	Quantity	0
Shen et al., (2022)	Quantity	+
Shen & Lung (2018)	Structural features	+
Vaz et al., (2020)	Structural features & tree canopy cover	+
Self-Harm		
Lee et al., (2023)	Tree canopy cover	+
Min et al., (2017)	Quantity	+
Srugo et al., (2019)	Level of greenness	0
Moran et al., (2021)	Quantity	+
Polling et al., (2019)	Quantity	0
Suicidal ideation		
Holman et al., (2022)	Duration	0
Iwata et al., (2016)	Frequency and duration	+
Min et al., (2017)	Quantity	+
Srugo et al., (2019)	Level of greenness	0
Sturm et al., (2012)	Frequency and duration	+
Yao et al., (2022)	Quantity	+

Note: The direction of the association is denoted by '+' for a protective association when there is at least one positive association across greenspace indicators, '0' for no association, '−' for a harmful association when there is at least one negative association across greenspace indicators.

[a]Results for total sample not reported. For females, increasing levels of greenspace were associated with more suicide mortality, whereas for males, the level of greenspace was not associated with suicide mortality. See Supplement Table S7.

Table 5. Associations between greenspace and suicide mortality by sex (*n*=10 of the included studies)

	Females	Males
Level of greenness		
Arsi et al., (2023)	Increasing levels of greenness was associated with lower suicide mortality (RR=0.81, 95%CI[0.75-0.88])	Increasing levels of greenness was associated with lower suicide mortality (RR=0.57, 95%CI[0.44,0.76])
Hagedoorn et al., (2022)	Living in neighbourhoods with high levels of greenspace or experiencing an increase in levels of greenspace are associated with higher suicide mortality rates (HR=1.14, 95% CI=[1.04–1.24] and HR=1.17, 95% CI=[1.01–1.34], respectively), compared to those having stable low levels of greenspace	Living in neighbourhoods with high levels of greenspace (HR= 1.06, 95%CI= [1.00-1.13]), experiencing an increase in levels of greenspace (HR=1.06, 95%CI=[0.96-1.17]), or experiencing a decrease in levels of greenspace (HR=1.04, 95%CI=[0.95-1.15]) was not associated with suicide mortality, compared to those having stable low levels of greenspace
Helbich et al., (2020)	Inter-quartile increments of NDVI in 300, 600, or 1000 m buffers did not decrease the odds of suicide mortality in the highest quartile of greenspace OR= 1.08, 95%CI [0.92-1.26]; OR= 1.04, 95%CI [0.88-1.23]; OR= 0.97, 95%CI [0.82-1.16], respectively	Inter-quartile increments of NDVI in 300, 600, or 1000 m buffers did not decrease the odds of suicide mortality in the highest quartile of greenspace OR= 1.02, 95%CI [0.92-1.14]; OR= 1.02, 95%CI [0.92-1.15]; OR= 1.02, 95%CI [0.91-1.15], respectively
Mendoza et al., (2022)	At buffers of 300m and 1000m, residential greenness was associated with lower suicide mortality: HR=0.81, 95%CI[0.75,0.87]; HR=0.78, 95%CI[0.73,0.85], respectively	At buffers of 300m and 1000m, residential greenness was not associated with lower suicide mortality: HR=0.99, 95%CI[0.94,1.04]; HR=1.01, 95%CI[0.96,1.06], respectively
Quantity of greenspace		
Bixby et al., (2015)	No association observed between the greenest versus least green urban areas and suicide mortality (RR= 1.10, 95%CI [0.77-1.57])	No association observed between the greenest versus least green urban areas and suicide mortality (RR= 1.02, 95%CI [0.85-1.23])

Jiang, Stickley & Ueda, (2022)	In large cities, park density (but not park coverage nor woodland coverage) was associated with lower suicide mortality for females aged 18-39 years (coef.= -0.62, SD= 0.18. p<0.001); 40-64 years (coef.= -0.39, SD= 0.20, p< 0.05) and 65+ years (coef.= -1.24, SD= 0.19, p< 0.001). In small/medium cities, park coverage was associated with lower suicide mortality in females aged 40-64 years (coef.= -4.19, SD=1.95, p<0.05) and 65+ years (coef.= -5.08, SD=1.37, p<0.001)	In large cities, park density (but not park coverage nor woodland coverage) was associated with lower suicide mortality for men aged 18-39 years (coef.= -0.51, SD= 0.18. p<0.01) and 65+ years (coef.= -0.64, SD= 0.22, p< 0.01). In small/medium cities, park density was associated with lower suicide mortality in men aged 65+ years (coef.= -0.07, SD=0.03, p<0.05). In rural areas, woodland coverage was associated with lower suicide mortality in men aged 40-64 years (coef.= -3.32, SD=1.35, p<0.05) and 65+ years (coef.= -3.44, SD=1.73, p<0.05)
Kim et al., (2022)	With every increase in 1 m2 per person in park area, the suicide mortality rate per 100,000 people decreased by -0.73 (t= -3.79, p<0.001)	No association between park area and the suicide mortality rate per 100,000 people (rate= -0.17, t= -0.65, p>0.05)
Shen, Lung & Cui, (2022)	Increasing green coverage was associated with lower suicide mortality (coef.= -0.20, 95%CI= [-0.27, 0.13]	Increasing green coverage was associated with lower suicide mortality (coef.= -0.20, 95%CI= [-0.29, 0.13]
Structural Features of greenspace		
Shen & Lung (2018)	Higher greenspace fragmentation (STEC= 0.14, p<0.01) and longer green patch distance (STEC= 0.42, p<0.001) increased the suicide mortality rate, while a larger green patch area (STEC= -0.21, <0.001) would decrease the suicide mortality rate	Higher greenspace fragmentation (STEC= 0.76, p<0.001) increased the suicide mortality rate
Vaz et al., (2020)	An increase of the following landscape metrics was correlated with less suicide mortality: grass/shrub percentage of landscape (β=-0.27, p< 0.001), grass/shrub mean patch area (β= -0.28, p< 0.01), grass/shrub clumpiness index (β= -0.24, p< 0.001) grass/shrub percentage of like adjacencies (β= -0.27, p< 0.001), and grass/shrub aggregation index (β= -0.27, p< 0.001). An increase in grass/shrub patch density (β= 0.22, p< 0.01) and grass/shrub perimeter area ratio (β= 0.27,	An increase in grass/shrub patch density (β= 0.14, p< 0.05) was correlated with more suicide mortality. All other grass/shrub measures were not statistically significant with male suicide mortality

	$p < 0.001$) was correlated with more suicide mortality	
Percentage of tree canopy		
Vaz et al., (2020)	Increased tree canopy landscape shape was correlated with less suicide mortality ($\beta = -0.21$, $p < 0.01$). Increased perimeter area ratio was correlated with more suicide mortality ($\beta = 0.33$, $p < 0.001$)	Increased tree canopy landscape shape was correlated with less suicide mortality ($\beta = -0.29$, $p < 0.05$). Increased perimeter area ratio was correlated with more suicide mortality ($\beta = 0.29$, $p < 0.001$)

Note: RR= Relative Risk. CI= Confidence Interval. OR= Odds Ratio. HR= Hazard Ratio. STEC= Standardized Total Effect Coefficient. RR= Relative Risk Ratio. Coef.= Coefficient

References

1. Frangione, B., et al., *Short-term changes in meteorological conditions and suicide: A systematic review and meta-analysis.* Environmental research, 2022. **207**: p. 112230.
2. Buoli, M., et al., *Is there a link between air pollution and mental disorders?* Environment international, 2018. **118**: p. 154-168.
3. Sui, Y., D. Ettema, and M. Helbich, *Longitudinal associations between the neighborhood social, natural, and built environment and mental health: A systematic review with meta-analyses.* Health & Place, 2022. **77**: p. 102893.
4. Labib, S., S. Lindley, and J.J. Huck, *Scale effects in remotely sensed greenspace metrics and how to mitigate them for environmental health exposure assessment.* Computers, Environment Urban Systems, 2020. **82**: p. 101501.
5. Zhang, J., et al., *Links between green space and public health: a bibliometric review of global research trends and future prospects from 1901 to 2019.* Environmental Research Letters, 2020. **15**(6): p. 063001.
6. Houlden, V., et al., *The relationship between greenspace and the mental wellbeing of adults: A systematic review.* PloS one, 2018. **13**(9): p. e0203000.
7. Vanaken, G.-J. and M. Danckaerts, *Impact of green space exposure on children's and adolescents' mental health: A systematic review.* International Journal of Environmental Research Public Health, 2018. **15**(12): p. 2668.
8. Zhang, Y., et al., *The association between green space and adolescents' mental well-being: a systematic review.* International Journal of Environmental Research Public Health, 2020. **17**(18): p. 6640.

9. Zhang, R., C.-Q. Zhang, and R.E. Rhodes, *The pathways linking objectively-measured greenspace exposure and mental health: A systematic review of observational studies.* Environmental Research, 2021. **198**: p. 111233.

10. Gianfredi, V., et al., *Association between urban greenspace and health: a systematic review of literature.* International Journal of Environmental Research and Public Health, 2021. **18**(10): p. 5137.

11. de Keijzer, C., M. Bauwelinck, and P. Dadvand, *Long-term exposure to residential greenspace and healthy ageing: a systematic review.* Current Environmental Health Reports, 2020. **7**(1): p. 65-88.

12. Sakhvidi, M.J.Z., et al., *Greenspace exposure and children behavior: A systematic review.* Science of the Total Environment, 2022: p. 153608.

13. Gascon, M., et al., *Mental health benefits of long-term exposure to residential green and blue spaces: a systematic review.* International journal of environmental research and public health, 2015. **12**(4): p. 4354-4379.

14. Fyfe-Johnson, A.L., et al., *Nature and children's health: a systematic review.* Pediatrics, 2021. **148**(4).

15. Kotera, Y., et al., *Effect of nature walks on depression and anxiety: a systematic review.* Sustainability, 2021. **13**(7): p. 4015.

16. Liu, Z., et al., *Green space exposure on depression and anxiety outcomes: A meta-analysis.* Environmental Research, 2023: p. 116303.

17. Sarkar, C., C. Webster, and J. Gallacher, *Residential greenness and prevalence of major depressive disorders: a cross-sectional, observational, associational study of 94 879 adult UK Biobank participants.* The Lancet Planetary Health, 2018. **2**(4): p. e162-e173.

18. Engemann, K., et al., *Residential green space in childhood is associated with lower risk of psychiatric disorders from adolescence into adulthood.* Proceedings of the National Academy of Sciences, 2019. **116**(11): p. 5188-5193.

19. Mueller, W., et al., *Urban greenspace and the indoor environment: Pathways to health via indoor particulate matter, noise, and road noise annoyance.* Environmental research, 2020. **180**: p. 108850.

20. Hartig, T., et al., *Nature and health.* Annual Review of Public Health, 2014. **35**: p. 207-228.

21. Markevych, I., et al., *Exploring pathways linking greenspace to health: Theoretical and methodological guidance.* Environmental Research, 2017. **158**: p. 301-317.

22. Schmutte, T., et al., *Comparisons between suicide in persons with serious mental illness, other mental disorders, or no known mental illness: Results from 37 US states, 2003–2017.* Schizophrenia research, 2021. **228**: p. 74-82.

23. Mullins, N., et al., *GWAS of suicide attempt in psychiatric disorders and association with major depression polygenic risk scores.* American Journal of Psychiatry, 2019. **176**(8): p. 651-660.

24. Helbich, M., et al., *Natural environments and suicide mortality in the Netherlands: a cross-sectional, ecological study.* The Lancet Planetary Health, 2018. **2**(3): p. e134-e139.

25. Min, K.-b., et al., *Parks and green areas and the risk for depression and suicidal indicators.* International Journal of Public Health, 2017. **62**(6): p. 647-656.

26. Helbich, M., et al., *Greenery exposure and suicide mortality later in life: a longitudinal register-based case-control study.* Environment International, 2020. **143**: p. 105982.

27. Bixby, H., et al., *Associations between green space and health in English cities: an ecological, cross-sectional study.* PLoS One, 2015. **10**(3): p. e0119495.

28. Sillman, D., et al., *Do sex and gender modify the association between green space and physical health? A systematic review.* Environmental Research, 2022. **209**: p. 112869.

29. Jimenez, M.P., et al., *Residential green space and cognitive function in a large cohort of middle-aged women.* JAMA Network Open, 2022. **5**(4): p. e229306-e229306.

30. Mendoza, H., et al., *Urban green spaces and suicide mortality in Belgium (2001–2011): A census-based longitudinal study.* Environmental research, 2023. **216**: p. 114517.

31. Vigo, D., G. Thornicroft, and R. Atun, *Estimating the true global burden of mental illness.* The Lancet Psychiatry, 2016. **3**(2): p. 171-178.

32. Statistics Canada, *Table 13-10-0394-01 Leading causes of death, total population, by age group.*

33. World Health Organization. *Suicide Data*. 2017; Available from: https://www.who.int/news-room/fact-sheets/detail/suicide.

34. Cuthbert, S., A. Kellas, and L.A. Page, *Green care in psychiatry.* The British Journal of Psychiatry, 2021. **218**(2): p. 73-74.

35. Page, M.J., et al., *PRISMA 2020 explanation and elaboration: updated guidance and exemplars for reporting systematic reviews.* BMJ, 2021. **372**.

36. Polanin, J.R., et al., *Best practice guidelines for abstract screening large-evidence systematic reviews and meta-analyses.* Research Synthesis Methods, 2019. **10**(3): p. 330-342.

37. Chiabai, A., et al., *Exposure to green areas: Modelling health benefits in a context of study heterogeneity.* Ecological Economics, 2020. **167**: p. 106401.

38. Nutsford, D., A. Pearson, and S. Kingham, *An ecological study investigating the association between access to urban green space and mental health.* Public Health, 2013. **127**(11): p. 1005-1011.

39. Nieuwenhuijsen, M. and H. Khreis, *Green Space and Health*, in *Integrating Human Health into Urban and Transport Planning: A Framework*. 2019, Springer International Publishing: Cham, Switzerland. p. 409–423.

40. Li, D. and W.C. Sullivan, *Impact of views to school landscapes on recovery from stress and mental fatigue.* Landscape Urban Planning, 2016. **148**: p. 149-158.

41. Hystad, P., et al., *Green space associations with mental health and cognitive function: Results from the Québec CARTaGENE cohort.* Environmental Epidemiology, 2019. **3**(1): p. e040.

42. Akpinar, A., *How is quality of urban green spaces associated with physical activity and health?* Urban Forestry Urban Greening, 2016. **16**: p. 76-83.

43. Gledhill, A., D. Forsdyke, and E. Murray, *Psychological interventions used to reduce sports injuries: a systematic review of real-world effectiveness.* British Journal of Sports Medicine, 2018. **52**(15): p. 967-971.

44. Hong, Q.N., et al., *Mixed methods appraisal tool (MMAT), version 2018.* Registration of copyright, 2018. **1148552**(10).

45. Hong, Q.N., et al., *The Mixed Methods Appraisal Tool (MMAT) version 2018 for information professionals and researchers.* Education for information, 2018. **34**(4): p. 285-291.

46. Hong, Q.N., et al., *Improving the content validity of the mixed methods appraisal tool: a modified e-Delphi study.* Journal of clinical epidemiology, 2019. **111**: p. 49-59. e1.

47. Souto, R.Q., et al., *Systematic mixed studies reviews: updating results on the reliability and efficiency of the mixed methods appraisal tool.* Int J Nurs Stud, 2015. **52**(1): p. 500-501.

48. Mitchell, R. and F. Popham, *Effect of exposure to natural environment on health inequalities: an observational population study.* The Lancet, 2008. **372**(9650): p. 1655-1660.

49. Moran, D., et al., *Does Nature Contact in Prison Improve Well-Being? Mapping Land Cover to Identify the Effect of Greenspace on Self-Harm and Violence in Prisons in England and Wales.* Annals of the American Association of Geographers, 2020: p. 1-17.

50. Polling, C., et al., *Spatial patterning of self-harm rates within urban areas.* Social Psychiatry Psychiatric Epidemiology, 2019. **54**(1): p. 69-79.

51. Shen, Y.-S. and S.-C.C. Lung, *Identifying critical green structure characteristics for reducing the suicide rate.* Urban Forestry Urban Greening, 2018. **34**: p. 147-153.

52. Srugo, S.A., et al., *Assessing the impact of school-based greenness on mental health among adolescent students in Ontario, Canada.* International Journal of Environmental Research Public Health, 2019. **16**(22): p. 4364.

53. Sturm, J., et al., *Physical exercise through mountain hiking in high-risk suicide patients. A randomized crossover trial.* Acta Psychiatrica Scandinavica, 2012. **126**(6): p. 467-475.

54. Hagedoorn, P. and M. Helbich, *Longitudinal effects of physical and social neighbourhood change on suicide mortality: A full population cohort study among movers and non-movers in the Netherlands.* Social Science & Medicine, 2022. **294**: p. 114690.

55. Holman, S., et al., *The association of social, economic, and health-related variables with suicidal and/or self-harm thoughts in individuals admitted to a psychiatric inpatient unit during the COVID-19 pandemic: An exploratory study.* Psychiatry research, 2023. **319**: p. 114998.

56. Shen, Y.-S., S.-C.C. Lung, and S. Cui, *Exploring multiple pathways and mediation effects of urban environmental factors for suicide prevention.* Environmental Pollution, 2022. **294**: p. 118642.

57. Jiang, W., A. Stickley, and M. Ueda, *Green space and suicide mortality in Japan: An ecological study.* Social Science & Medicine, 2021. **282**: p. 114137.

58. Asri, A.K., et al., *Examining the benefits of greenness on reducing suicide mortality rate: A global ecological study.* Frontiers in public health, 2022. **10**.

59. Jiang, B., et al., *A natural experiment reveals impacts of built environment on suicide rate: Developing an environmental theory of suicide.* Science of the Total Environment, 2021. **776**: p. 145750.

60. Kim, U.-R. and H. Sung, *Urban parks as a potential mitigator of suicide rates resulting from global pandemics: Empirical evidence from past experiences in Seoul, Korea.* Cities, 2022. **127**: p. 103725.

61. Lee, S., R.J. Lee, and S. Scherr, *How tree canopy cover can reduce urban suicide attempts: A geospatial analysis of the moderating role of area deprivation.* Landscape and Urban Planning, 2023. **230**: p. 104606.

62. Vaz, E., R.R. Shaker, and M.D. Cusimano, *A geographical exploration of environmental and land use characteristics of suicide in the greater Toronto area.* Psychiatry research, 2020. **287**: p. 112790.

63. Yao, Y., et al., *Can parkland mitigate mental health burden imposed by the COVID-19? A national study in China.* Urban Forestry & Urban Greening, 2022. **67**: p. 127451.

64. Iwata, Y., et al., *Benefits of group walking in forests for people with significant mental ill-health.* Ecopsychology, 2016. **8**(1): p. 16-26.

65. El-Mallakh, T.V., et al., *Suicide and Homicide More Common with Limited Urban Tree Canopy Cover.* Cities and the Environment (CATE), 2022. **14**(2): p. 4.

66. Hajna, S., V. Nafilyan, and S. Cummins, *Associations between residential greenspace exposure and mortality in 4 645 581 adults living in London, UK: a longitudinal study.* The Lancet Planetary Health, 2023. **7**(6): p. e459-e468.

67. Jarvis, I., et al., *Greenspace access does not correspond to nature exposure: Measures of urban natural space with implications for health research.* Landscape and Urban Planning, 2020. **194**: p. 103686.

68. Bolte, G., S. Nanninga, and L. Dandolo, *Sex/gender differences in the association between residential green space and self-rated health—A sex/gender-focused systematic review.* International journal of environmental research and public health, 2019. **16**(23): p. 4818.

69. Akpinar, A., C. Barbosa-Leiker, and K.R. Brooks, *Does green space matter? Exploring relationships between green space type and health indicators.* Urban Forestry & Urban Greening, 2016. **20**: p. 407-418.

70. Maes, M.J., et al., *Benefit of woodland and other natural environments for adolescents' cognition and mental health.* Nature Sustainability, 2021. **4**(10): p. 851-858.

71. Ha, J., H.J. Kim, and K.A. With, *Urban green space alone is not enough: A landscape analysis linking the spatial distribution of urban green space to mental health in the city of Chicago.* Landscape and Urban Planning, 2022. **218**: p. 104309.

72. O'Connor, R.C. and O.J. Kirtley, *The integrated motivational–volitional model of suicidal behaviour.* Philosophical Transactions of the Royal Society B: Biological Sciences, 2018. **373**(1754): p. 20170268.

73. Turecki, G., et al., *Suicide and suicide risk.* Nature reviews Disease primers, 2019. **5**(1): p. 74.

74. Nguyen, P.-Y., et al., *Effect of nature prescriptions on cardiometabolic and mental health, and physical activity: a systematic review.* The Lancet Planetary Health, 2023. **7**(4): p. e313-e328.

75. Watkins-Martin, K., et al., *The effects of walking in nature on negative and positive affect in adult psychiatric outpatients with major depressive disorder: A randomized-controlled study.* medRxiv, 2021.

76. Wang, P., et al., *Association of urban built environment and socioeconomic factors with suicide mortality in high-density cities: A case study of Hong Kong.* Science of the total environment, 2020. **739**: p. 139877.

77. Silva, J.A.C. and R.E. Steffen, *Urban environment and psychiatric disorders: a review of the neuroscience and biology.* Metabolism, 2019. **100**: p. 153940.

78. Cohen-Cline, H., E. Turkheimer, and G.E. Duncan, *Access to green space, physical activity and mental health: a twin study.* J Epidemiol Community Health, 2015. **69**(6): p. 523-529.

79. Kivimäki, M., et al., *Association between socioeconomic status and the development of mental and physical health conditions in adulthood: a multi-cohort study.* The Lancet Public Health, 2020. **5**(3): p. e140-e149.

80. Astell-Burt, T., et al., *Do low-income neighbourhoods have the least green space? A cross-sectional study of Australia's most populous cities.* BMC public health, 2014. **14**: p. 1-11.

81. Mitchell, R.J., et al., *Neighborhood environments and socioeconomic inequalities in mental well-being.* American journal of preventive medicine, 2015. **49**(1): p. 80-84.

82. Feng, X. and T. Astell-Burt, *The relationship between neighbourhood green space and child mental wellbeing depends upon whom you ask: multilevel evidence from 3083 children aged 12–13 years.* International journal of environmental research and public health, 2017. **14**(3): p. 235.

83. Cardinali, M., et al., *Preferred reporting items in green space health research. Guiding principles for an interdisciplinary field.* Environmental Research, 2023: p. 115893.

84. Ulrich, R.S., et al., *Stress recovery during exposure to natural and urban environments.* Journal of Environmental Psychology, 1991. **11**(3): p. 201-230.

85. Kaplan, R. and S. Kaplan, *The experience of nature: A psychological perspective*. 1989: Cambridge university press.

86. Labib, S., S. Lindley, and J.J. Huck, *Spatial dimensions of the influence of urban green-blue spaces on human health: A systematic review.* Environmental Research, 2020. **180**: p. 108869.

87. Openshaw, S., *The modifiable areal unit problem.* Concepts and techniques in modern geography, 1984.

88. Marceau, D.J., *The scale issue in the social and natural sciences.* Canadian Journal of Remote Sensing, 1999. **25**(4): p. 347-356.

89. Weigand, M., et al., *Remote sensing in environmental justice research—a review.* ISPRS International Journal of Geo-Information, 2019. **8**(1): p. 20.

90. Piantadosi, S., D.P. Byar, and S.B. Green, *The ecological fallacy.* American journal of epidemiology, 1988. **127**(5): p. 893-904.

91. Jia, P., et al., *Spatial lifecourse epidemiology reporting standards (ISLE-ReSt) statement.* Health & place, 2020. **61**: p. 102243.

92. Braubach, M., et al., *Green and blue spaces and mental health: New evidence and perspectives for action.* 2021.

93. Crank, P.J., D.M. Hondula, and D.J. Sailor, *Mental health and air temperature: Attributable risk analysis for schizophrenia hospital admissions in arid urban climates.* Science of The Total Environment, 2023. **862**: p. 160599.

94. Haggerty, J.L., et al., *An exploration of rural–urban differences in healthcare-seeking trajectories: Implications for measures of accessibility.* Health & place, 2014. **28**: p. 92-98.

95. Fleet, R., et al., *Portrait of rural emergency departments in Québec and utilization of the provincial emergency department management Guide: cross sectional survey.* BMC health services research, 2015. **15**(1): p. 1-9.

96. Zhou, P., et al., *Impacts of Social Inequality, Air Pollution, Rural–Urban Divides, and Insufficient Green Space on Residents' Health in China: Insight from Chinese General Social Survey Data Analysis.* International Journal of Environmental Research and Public Health, 2022. **19**(21): p. 14225.

97. Wolff, M., S. Scheuer, and D. Haase, *Looking beyond boundaries: Revisiting the rural-urban interface of Green Space Accessibility in Europe.* Ecological Indicators, 2020. **113**: p. 106245.

98. Casant, J. and M. Helbich, *Inequalities of suicide mortality across urban and rural areas: A literature review.* International journal of environmental research and public health, 2022. **19**(5): p. 2669.

99. Wood, C., C. Wicks, and J. Barton, *Green spaces for mental disorders.* Current Opinion in Psychiatry, 2023. **36**(1): p. 41-46.

100. Madigan, S., et al., *Comparison of paediatric emergency department visits for attempted suicide, self-harm, and suicidal ideation before and during the COVID-19 pandemic: a systematic review and meta-analysis.* The Lancet Psychiatry, 2023.

Appendix

Table of Contents

Table A1. PyscInfo (Ovid, 1806-Present) search strategy executed on January 6, 2023

1. *Suicide/	35. greenway*.mp.
2. exp Self-Injurious Behavior/	36. green belt*.mp.
3. exp Self-Mutilation/	37. green corridor*.mp.
4. exp Suicidal Ideation/	38. park.ti,ab.
5. exp Attempted Suicide/	39. parks.ti,ab.
6. *Self-Destructive Behavior/	40. natur* space*.mp.
7. exp Suicidality/	41. naturalness.mp.
8. self injur*.ti,ab.	42. garden*.mp.
9. self mutilat*.ti,ab.	43. exp Horticulture Therapy/
10. auto mutilat*.ti,ab.	44. exp Playgrounds/
11. para suicid*.ti,ab.	45. playground*.mp.
12. self poison*.ti,ab.	46. canopy.mp.
13. self injurious behavio*.ti,ab.	47. woodland*.mp.
14. suicid*.ti.	48. urban nature.mp.
15. self harm*.ti,ab.	49. school green*.mp.
16. self destruct*.ti,ab.	50. residential green*.mp.
17. suicid* mortalit*.ti,ab.	51. Normalized difference vegetation index.mp.
18. suicid* thought*.ti,ab.	52. ndvi.mp.
19. 1 or 2 or 3 or 4 or 5 or 6 or 7 or 8 or 9 or 10 or 11 or 12 or 13 or 14 or 15 or 16 or 17 or 18	53. 20 or 21 or 22 or 23 or 24 or 25 or 26 or 27 or 28 or 29 or 30 or 31 or 32 or 33 or 34 or 35 or 36 or 37 or 38 or 39 or 40 or 41 or 42 or 43 or 44 or 45 or 46 or 47 or 48 or 49 or 50 or 51 or 52
20. greenspace*.mp.	54. 19 and 53 (2156)
21. green space*.mp.	55 built environment.mp. or Built Environment/
22. greenness.mp.	56 “land use”.mp.
23. greenery.mp.	57 urban environment.mp.
24. tree cover*.mp.	58 urban space.mp.
25. *"Nature (Environment)"/	59 53 or 54 or 55 or 56
26. natural environment*.mp.	60 19 and 59 (393)
27. nearby nature.mp.	
28. nature.mp.	
29. hiking.mp.	
30. exp Camping/	
31. camping.mp.	
32. *Recreation Areas/	
33. exp Wilderness Experience/	
34. green area*.mp.	

Table A2. MEDLINE (Ovid, 1946-Present) search strategy executed on January 6, 2023

1	*Suicide/
2	*Self-Injurious Behavior/
3	exp Self Mutilation/
4	exp Suicidal Ideation/
5	exp Suicide, Attempted/
6	self injur*.ti,ab.
7	self mutilat*.ti,ab.
8	auto mutilat*.ti,ab.
9	para suicid*.ti,ab.
10	self poison*.ti,ab.
11	self injurious behavio*.ti,ab.
12	suicid*.ti.
13	self harm*.ti,ab.
14	self destruct*.ti,ab.
15	suicid* mortalit*.ti,ab.
16	suicid* thought*.ti,ab.
17	1 or 2 or 3 or 4 or 5 or 6 or 7 or 8 or 9 or 10 or 11 or 12 or 13 or 14 or 15 or 16 (75805)
18	greenspace*.mp.
19	green space*.mp.
20	greenness.mp.
21	greenery.mp.
22	tree cover*.mp.
23	natural environment*.mp.
24	nearby nature.mp.
25	nature.mp.
26	hiking.mp.
27	Camping/
28	camping.mp.
29	Wilderness/
30	green area*.mp.
31	greenway*.mp.
32	green belt*.mp.
33	green corridor*.mp.
34	park.ti,ab.
35	parks.ti,ab.
36	natur* space*.mp.
37	naturalness.mp.
38	garden*.mp.
39	*Horticulture/
40	Gardening/
41	Parks, Recreational/
42	playground*.mp.
43	canopy.mp.
44	woodland*.mp.
45	urban nature.mp.
46	school green*.mp.
47	residential green*.mp.
48	Normalized difference vegetation index.mp.
49	ndvi.mp.
50	18 or 19 or 20 or 21 or 22 or 23 or 24 or 25 or 26 or 27 or 28 or 29 or 30 or 31 or 32 or 33 or 34 or 35 or 36 or 37 or 38 or 39 or 40 or 41 or 42 or 43 or 44 or 45 or 46 or 47 or 48 or 49
51	17 and 50 (1817)
52	built environment.mp. or Built Environment/
53	“land use”.mp.
54	urban environment.mp.
55	urban space.mp.
57	53 or 54 or 55 or 56
58	17 and 57 (29)

Table A3. Web of Science search strategy executed on January 6, 2023

TS=(Suicide OR suicidal* OR "Self-Injurious Behavio*r" OR "Self Injurious Behavio*r" OR "Self-Mutilat*" OR "self mutilat*" OR "self-injur*" OR "self injur*" OR "Self-Destructive Behavio*r" OR "Self Destructive Behavio*r" OR "auto mutilat*" OR "auto-mutilat*" OR "self poison*" OR "self-poison*" OR "self harm*" OR "self-harm*" OR "self destruct*" OR "self-destruct*")

AND

TS=(greenspace* OR "green space*" OR greenness OR greenery OR "tree cover*" OR "natural environment*" OR hiking OR camping OR "wilderness experience*" OR "green area*" OR greenway* OR "green belt*" OR "green corridor*" OR "natur* space*" OR naturalness OR garden* OR horticulture OR playground* OR canopy OR woodland* OR "school green*" OR "residential green*" OR "Normalized difference vegetation index" OR ndvi OR nature)

OR

TI=(Park*)

OR

AB=(Park*)

Table A4. Excluded studies after scanning the full texts

Reasons for exclusion	**Number of studies**
No greenspace measure (i.e., objective or subjective) [1-7]	7
Mix of indoor/outdoor greenspace with no outdoor greenspace estimate [8]	1
Measured mental well-being and not a suicide-related outcome [9] or measured wrong outcome [10]	2
Student dissertation [11] and published study protocol [12]	2

Table A5. Quality assessment ratings of the included studies using the Mixed Methods Appraisal Tool (MMAT)

First author	2.1. Is randomization appropriately performed?	2.2. Are the groups comparable at baseline?	2.3. Are there complete outcome data?	2.4. Are outcome assessors blinded to the intervention provided?	2.5 Did the participants adhere to the assigned intervention?	3.1. Are the participants representative of the target population?	3.2. Are measurements appropriate regarding both the outcome and intervention (or exposure)?	3.3. Are there complete outcome data?	3.4. Are the confounders accounted for in the design and analysis?	3.5. During the study period, is the intervention administered (or exposure occurred) as intended?
Asri et al., (2023)						Yes	Yes	Yes	Yes	Yes
Bixby et al., (2022)						Yes	Yes	Yes	Yes	Yes
El-Mallakh et al., (2022)						Yes	Yes	Yes	Yes	Can't tell
Hagedoorn et al., (2022)						Yes	Yes	Yes	Yes	Yes
Helbich et al., (2018)						Yes	Yes	Yes	Yes	No
Helbich et al., (2020)						Yes	Yes	Yes	Yes	Yes
Holman et al., (2023)						No	No	No	Yes	Can't tell
Iwata et al., (2016)						No	No	Yes	No	Yes
Jiang et al., (2021)						Yes	Yes	Yes	Yes	Yes
Jiang, Stickley & Ueda (2021)						Yes	Yes	Yes	Yes	Yes
Kim et al., (2022)						Yes	Yes	Yes	Yes	Yes

Lee et al., (2023)						Yes	Yes	Yes	Yes	Yes
Mendoza et al., (2022)						Yes	Yes	Yes	Yes	Yes
Min et al., (2017)						Yes	Yes	Yes	Yes	Yes
Mitchell & Popham., (2008)						Yes	Yes	Yes	Yes	No
Moran et al., (2021)						Yes	Yes	Yes	Yes	Yes
Polling et al., (2019)						Yes	Yes	Yes	Yes	Can't tell
Shen & Lung (2018)						Yes	Yes	Yes	No	Yes
Shen. Lung & Cui (2012)						Yes	Yes	Yes	No	Yes
Sturm et al., (2012)	Yes	Yes	Yes	Yes	Yes					
Srugo et al., (2019)						Yes	Yes	Yes	Yes	No
Vaz et al., (2020)						Yes	Yes	Yes	No	Can't tell
Yao et al., (2022)						Can’t tell	Yes	Can't tell	Yes	Yes

Table A6. Suicide-related outcome measures in the included studies (*n*=23)

	Suicide-Related Outcomes			
	Mortality	Self-Harm	Ideation	Assessment Method
Asri et al., (2022)	Yes	No	No	Registered deaths (ICD-10 codes X60-X84)
Bixby et al., (2015)	Yes	No	No	Registered deaths (ICD-10 codes X60-X84)
El-Mallakh et al., (2022)	Yes	No	No	Medical examiner's report between 2007-2017 and expressed per population of home zip code
Hagedoorn et al., (2022)	Yes	No	No	Registered deaths (ICD-10 codes X60-X84)
Helbich et al., (2018)	Yes	No	No	Registered suicide deaths (ICD-10 codes X60.0–X84.9)
Helbich et al., (2020)	Yes	No	No	Registered suicide deaths (ICD-10 codes X60.0–X84.9)
Holman et al., (2023)	No	No	Yes	Suicidal ideation measured via following question: "Since the official lockdown was announced on March 14, 2020, have you had thoughts you would be better off dead or of hurting yourself in some way?"
Iwata et al., (2016)	No	No	Yes	Beck Depression Inventory and the Hamilton Depression Rating Scale
Jiang et al., (2021)	Yes	No	No	Deaths recorded by the Coroner's Court of Hong Kong between 2005-2017
Jiang, Stickley & Ueda (2021)	Yes	No	No	Registered suicide deaths (ICD-8/9 or 10 codes (E950-E959, X60.0–X84.9, respectively)
Kim et al., (2022)	Yes	No	No	Registered deaths with data obtained from the Korean Statistical Information service (2003-2018)

Lee et al., (2023)	No	Yes	No	Suicide attempt records at the Census block group level obtained from dispatch database of the Emergency Medical Services Calls in Ohio
Mendoza et al., (2022)	Yes	No	No	Registered deaths (ICD-10 codes X60-X84)
Min et al., (2017)	No	Yes	Yes	Past-year suicidal ideation and past-year suicide attempt(s) (each coded as yes versus no)
Mitchell & Popham (2008)	Yes	No	No	Registered deaths due to intentional self-harm (ICD-10 codes X60–X84)
Moran et al., (2021)	No	Yes	No	Registered incidents of self-harm (e.g., burning, cutting, hanging, poisoning) mandated by Her Majesty's Prison and Probation Service
Polling et al., (2019)	No	Yes	No	Registered admissions for self-harm defined as a first episode of inpatient care in a general hospital (ICD-10 codes X60–X84) between 2007-2016
Shen et al., (2022)	Yes	No	No	Registered deaths (ICD-10 codes X60-X84)
Shen & Lung (2018)	Yes	No	No	Adjudicated death certificates for suicide (definition of suicide based on ICD-10 classification)
Sturm et al., (2012)	No	No	Yes	Beck Scale for Suicide Ideation
Srugo et al., (2019)	No	Yes	Yes	Past-year suicidal ideation and past-year suicide attempt(s) (each coded as yes versus no)
Vaz et al., (2020)	Yes	No	No	Emergency Medical Service data with recorded suicides in 2002 and 2004
Yao et al., (2022)	No	No	Yes	Suicidal ideation index constructed via Baidu (most widely used search engine in China) based on average search frequency for the word “suicide”

Note: ICD-10= International Statistical Classification of Diseases and Related Health Problems 10th Revision.

Appendix References

1. Bettmann, J.E., et al., *Who are they? A descriptive study of adolescents in wilderness and residential programs.* Residential Treatment for Children & Youth, 2011. **28**(3): p. 192-210.
2. Bettmann, J.E., et al., *An exploration of gender, client history, and functioning in wilderness therapy participants.* Residential Treatment for Children & Youth, 2014. **31**(3): p. 155-170.
3. Wang, P., et al., *Association of urban built environment and socioeconomic factors with suicide mortality in high-density cities: A case study of Hong Kong.* Science of the Total Environment, 2020. **739**: p. 139877.
4. Warne, N., et al., *Disordered eating and self-harm as risk factors for poorer mental health during the COVID-19 pandemic: A population-based cohort study.* MedRxiv : the Preprint Server for Health Sciences, 2021. **04**: p. 04.
5. McLaren, S., *Rurality, reasons for living, and suicidal ideation among Australian men.* Death studies, 2022. **46**(8): p. 1853-1861.
6. Helbich, M., et al., *Urban–rural inequalities in suicide mortality: a comparison of urbanicity indicators.* International journal of health geographics, 2017. **16**: p. 1-12.
7. Kanamori, M. and N. Kondo, *Suicide and types of agriculture: a time-series analysis in Japan.* Suicide and Life-Threatening Behavior, 2020. **50**(1): p. 122-137.
8. Meore, A., et al., *Pilot Evaluation of Horticultural Therapy In Improving Overall Wellness in Veterans with History of Suicidality.* Complementary Therapies in Medicine, 2021: p. 102728.

9. Farrier, A., M. Baybutt, and M. Dooris, *Mental health and wellbeing benefits from a prisons horticultural programme.* International Journal of Prisoner Health, 2019. **15**(1): p. 91-104.

10. Moran, D., et al., *Nature contact in the carceral workplace: greenspace and staff sickness absence in prisons in England and Wales.* Environment and Behavior, 2022. **54**(2): p. 276-299.

11. Courtemanche, A., *A multi-component approach to reducing self-injury in the natural environment.* Dissertation Abstracts International: Section B: The Sciences and Engineering, 2013. **74**(6-B(E)): p. No Pagination Specified.

12. Hautekiet, P., et al., *Environmental exposures and health behavior in association with mental health: a study design.* Archives of Public Health, 2020. **78**(1): p. 9.

Bridging Between Chapter 3 and Chapter 4

In **Chapter 3**, our systematic review revealed that there was an observed beneficial association between greenspace exposure and suicide-related outcomes across the lifespan, with stronger associations for females. Importantly, the results from this review further highlighted that there is a need for research evaluating the associations between greenspace exposure and suicide-related outcomes in youth populations. Additionally, this review established that there is a paucity of knowledge regarding greenspace exposure and suicide-related outcomes in Canada. In response to these noted limitations, the aim of **Chapter 4** was to investigate the longitudinal associations of greenspace exposure in a sample of Canadian youth from the province of Québec, including a wide range of common internalizing (i.e., anxiety, depression, suicidal ideation) and externalizing (i.e., inattention, hyperactivity/impulsivity, conduct problems) mental health problem symptoms. Additional aims of this study were to evaluate effect modifications by family socioeconomic status and sex.

Chapter 4: Increased urban greenspace in childhood associated with lower inattention deficit among adolescents

Bolanis, D., Orri, M., Vergunst, F., Bouchard, S., Robitaille, É., Philippe, F., Ouellet-Morin, I., Girard, A., Paquin, V., Gauvin, L., Côté, S., & Geoffroy, M. C. (2023). Increased urban greenspace in childhood associated with lower inattention deficit among adolescents. *Social Psychiatry and Psychiatric Epidemiology*, 1-10. https://doi.org/10.1007/s00127-023-02575-0

Funding Sources: Mrs. Bolanis is funded by the Canada Graduate Scholarships Doctoral (CGS-D) Program for the Social Sciences and Humanities Research Council (SSHRC). Drs Ouellet-Morin and Geoffroy each hold a Canada Research Chair. This study was conducted with funding from the SSHRC (Drs Geoffroy, Philippe and Ouellet-Morin) and the Research team in suicide prevention Fonds de Recherche du Québec – Société et Culture – Papageno (Drs Geoffroy and Orri). The Québec Longitudinal Study of Child Development was supported by funding from the ministère de la Santé et des Services sociaux, le ministère de la Famille, le ministère de l'Éducation et de l'Enseignement supérieur, the Lucie and André Chagnon Foundation, the Institut de recherché Robert-Sauvé en santé et en sécurité du travail, the Research Centre of the Sainte-Justine University Hospital, the ministère du Travail, de l'Emploi et de la Solidarité sociale and the Institut de la statistique du Québec. Additional funding was received by the Fonds de Recherche du Québec - Santé (FRQS), the Fonds de Recherche du Québec - Société et Culture (FRQSC), the Social Science and Humanities Research Council of Canada (SSHRC), the Canadian Institutes of Health Research (CIHR).

Data Access: Data has been obtained from a third party. The data analyzed in this study was obtained from the Institut de la statistique du Québec, and as stipulated in clauses 10 and 11 of the Institut de la statistique's du Québec Act (Canada), the access to the data is restricted to the parties identified in the partnership agreement signed to ensure the conduct of the study and

which describes the author's right. In the QLSCD cohort, the participants only consented to share their data to the study's financial partners and affiliated researchers and their collaborators. Those partners and researchers only have access after signing a data sharing agreement. Requests to access these data can be directed to the Institut de la statistique du Québec's Research Data Access Services – Home (www.quebec.ca).

Abstract

Purpose: There is a growing interest in assessing the benefits of exposure to urban greenspace on mental health due to the increased urbanization of youth and concerns for their mental health. We investigated the prospective associations of residential greenspace in childhood and mental health in adolescence. Use of a well-characterized birth cohort permitted adjustment for a range of potential confounding factors including family and neighbourhood characteristics in addition to prior mental health problems, and exploration of moderation effects by sex and family socioeconomic status.

Methods: We analysed longitudinal data collected from 742 urban-dwelling participants of the Québec Longitudinal Study of Children Development. The Normalized Difference Vegetation Index (NDVI) within 250, 500 and 1000m buffer zones surrounding the home residence was used to indicate childhood exposure to greenspace. Six self-reported mental health problems at 15/17 years were examined using the Mental Health and Social Inadaptation questionnaire: inattention, hyperactivity/impulsivity, conduct, depression, anxiety and suicidal ideation.

Results: Childhood urban greenspace was associated with lower inattention problems in both females and males. We observed a 0.14 reduced standard deviation (SD) (β=-0.14,SE=0.05,p<0.01) in relation to an interquartile range (IQR) increase of NDVI (0.15) at the 250m buffer zone, similar results were found in 500m and 1000m buffer zones. These associations only slightly attenuated after adjustment for individual (sex, childhood mental health), family (family SES, maternal age at birth, parental mental health, family composition), and neighborhood (material and social deprivation) characteristics (β=-0.13,SE=0.06,p=0.03). No association was found for other mental health problems, and no moderation associations of sex or family socioeconomic status were observed.

Conclusion: These findings suggest that increasing residential greenspace in cities may be associated with modest benefits in attentional capacities in youth, necessitating further research to elucidate the underlying mechanisms.

Abbreviations: Normalized Difference Vegetation Index (NDVI); Interquartile range (IQR); Standard Deviation (SD); Attention-Deficit Hyperactivity Disorder (ADHD)

Introduction

Approximately 1.2 million Canadian youth are affected by at least one mental health problem [1] with the prevalence of depression and anxiety on the rise [2]. These alarming numbers bring to light the importance of identifying modifiable protective factors that could aid in alleviating mental health problems.

In recent years, the potential benefits of exposure to greenspace (i.e. natural or semi-natural outdoor area completely or partially covered by vegetation, such as parks, forests, trees, and woodlands [3]) for mental health have gained significant attention [4-6], especially for urban dwellers who are more likely to benefit from greenspace (in comparison to those residing in rural areas) as evidenced in a recent review [7]. The promotion of greenspace in urban landscapes may hold the potential to improve health since greenspace offers opportunities to reduce exposure to harmful exposures (e.g., air and noise pollution), restore attentional capacities, and encourage physical activity [8].

Prospective population-based studies are imperative to assess the long-term associations between greenspace and mental health, especially as they allow for the examination of individuals exposed to settings differing in levels of surrounding greenspace (most commonly measured using the Normalized Difference Vegetation Index; NDVI [9])
over long follow-up periods, and provide the ability to control for key confounding factors assessed prior to the exposure (e.g., childhood and parental mental health problems).

While some longitudinal population-based studies have found that increased greenspace exposure in childhood is associated with lower symptoms of depression [10, 11], anxiety [12], attention-deficit hyperactivity disorder (ADHD) [12-14], and conduct problems [12] in adolescence, other studies have not [15-17]. It is unclear whether or not the benefits of

greenspace exposure on mental health affect all youth equally, and if some groups (such as female vs. male, or socioeconomically advantaged vs. disadvantaged youth) benefit more than others. With respect to sex, some studies indicate associations between increased greenspace exposure and lower mental health problems among male but not female individuals [18], whereas other studies report inversed patterns of findings [14], or no differences [12, 19]. Although the mechanisms by which sex modifies the associations between greenspace and mental health remain unknown, previous systematic reviews have posited that physiological and psychological responses to greenness may differ across female and male individuals [20, 21]. At the same time, it has been suggested that individuals with mental health problems from disadvantaged socioeconomic backgrounds disproportionately benefit from higher greenspace exposure [22-25]; however, the few studies that investigated this question in youth have produced inconsistent results [13, 14, 26-29]. Additionally, several studies report associations between higher levels of residential greenspace and lower incidence of suicidal ideation and suicide mortality among adults [30-32] however, evidence drawn from adolescent populations is scarce [33].

Drawing from a representative sample of adolescents residing in urban regions of the province of Québec (Canada), this study had two aims. First, we aimed to investigate the associations of childhood residential greenspace with a range of mental health problems (i.e., inattention, hyperactivity/impulsivity, conduct problems, depression, anxiety, and suicidal ideation) with adjustment for factors at the individual, family, and neighborhood levels. Second, we examined whether these associations were moderated by sex and by disparities in levels of family socioeconomic status (SES).

Method

Participants

Participants were from the Québec Longitudinal Study of Child Development (QLSCD; conducted by Institut de la Statistique du Québec, ISQ), a population-based birth cohort of 2120 children born in Québec, Canada, in 1997-1998 and followed up annually or biannually since [34]. The Québec Master Birth Registry of the Minister of Health and Social Services was used to create a stratified random sample based on living area and birth rates [35]. At its inception, the QLSCD represented the Québec population of singleton births, including all ranges of socioeconomic status (SES). More information regarding the QLSCD can be found on https://www.iamillbe.stat.gouv.qc.ca/default_an.htm. The QLSCD protocol was approved by the Institut de la statistique du Québec and the St-Justine Hospital Research Centre ethics committees, and informed consent, assent, or both were obtained at each data collection.

Procedure

We used information on childhood residential greenspace at 10 years of age (2008) and mental health outcomes reported by the adolescents via an online questionnaire at 15 and 17 years of age (2013/2015) [36-38]. We selected children who were residing in urban regions of Québec (i.e., Montreal, Sherbrooke, Trois-Rivières, Gatineau and Saguenay; population size >100,000 habitants per region, except Montreal with >3 million habitants) in 2006/2008, accounting for 65% of all children participating in the QLSCD.

Adolescent Mental Health Problems

Mental health symptoms in the past year were assessed using the Mental Health and Social Inadaptation Assessment for Adolescents [39] (never=1; sometimes=2; often=3). Adolescents self-reported externalizing problems, namely inattention, hyperactivity/impulsivity, and conduct problems, and internalizing problems, namely depression, generalized anxiety, and

serious suicidal ideation ("did you ever seriously think of attempting suicide?"; yes=1, no=0). The six scales were z-standardized (Mean= 0, SD=1) and averaged across the two assessments to obtain a summary score for each problem during adolescence (i.e., 15 and 17 years). The items comprised in these scales, their internal consistencies, and their correlation matrix are presented in **Supplementary Tables S1** and **S2**.

Childhood Residential Greenspace

We retrieved the residential greenspace measure from the Canadian Urban Environment Health Research Consortium which was characterized using the Normalized Difference Vegetation Index (NDVI). NDVI quantifies vegetation by measuring the ratio between near-infrared light, which vegetation reflects, and red light, which vegetation absorbs [40]. Values from this index range between -1 to 1, with negative values representing water and/or cloud covering and/or inorganic objects, values around zero representing sparse and brown vegetation, and higher positive values representing dense and green vegetation. We used NDVI data from 2007 provided by the United States Geological Survey Landsat 8 satellite, with a spatial resolution of 30m accessed via Google Earth Engine [41-44]. Given substantial snow covering during the winter months in Québec, pixels with more than 20% cloud or snow were not included in the NDVI calculation and all bodies of water were masked.

NDVI values were available for 2007 and 6-digit-postal code information for QLSCD participants was available in 2006 and 2008. As such, we geocoded the NDVI values in 2007 with the children's 6-digit postal codes in 2008 or 2006 for the 71 participants with missing postal code information in 2008 (correlation between NDVI values from postal code information in 2008 and 2006 was 0.89, $p<0.001$; **Figure 1**); resulting in a cross-sectional NDVI assessment. The 6-digit postal code is the most precise unit in Canada that allows for the identification of

where individuals reside [45]; in urban regions, this is equivalent to one side of a city block (e.g., single apartment building) [46]. In the current study, there was no clustering of participants within 6-digit-postal codes (i.e., more than 98% of postal codes had a single participant allocated to it). Greenspace data were abstracted to produce measures corresponding to circular buffers of 250m, 500m, and 1000m around the centroid of each child's residential postal code. Our main analysis relied on the 250m buffer, and we modelled the maximum annual mean value obtained from across a series of pixels each having their own annual mean within this buffer. We also conducted sensitivity analyses using similarly derived maximum annual mean values with 500m and 1000m buffers.

Confounding factors

Confounding factors were selected based on their associations with mental health and/or greenspace exposure (**Supplement Table S3**) and were measured at 8 and 10 years of age with scores averaged across assessments (to maximize the total sample size), unless otherwise indicated.

Individual characteristics

Child sex (male/female) was reported by parents. Childhood mental health problems were reported by school teachers using the Social Behavior Questionnaire [47]: oppositional and defiant behavior (4 items; eg, defiant or refused to comply), inattention and hyperactivity (9 items; eg, "could not sit still"), and depressive and anxious symptoms (5 items, eg, fearful or sad). The items were derived from the Canadian National Longitudinal Study of Children and Youth [48], which incorporates items from the Child Behavior Checklist [49], with responses rated on a 3-point scale.

Family Characteristics

Maternal age at childbirth was recorded in years. Parental depressive symptoms in past week was assessed at 5 months using 12 items from the short form of the Centre for Epidemiological Study Depression Scale (12 items; eg, “I felt depressed”) [50]. Parental antisocial behaviors during adolescence were assessed using 5 retrospective conduct items (eg, having been in >1 fight that they started; having stolen >1 time) [51]. For all parental mental health problems, a mean score was derived based on the availability of data from at least one parent. SES was measured using a standardized aggregate index of five items relating to parents’ education level, occupational prestige, and gross annual household income [52]. The scale ranged from -3 to 3, centered at 0, with higher scores indicating higher SES. Family composition was categorized as intact (biological parents) or non-intact (single, separated, divorced, or widowed).

Neighborhood Characteristics

Neighborhood socioeconomic disadvantage was estimated using material and social deprivation indices based on census data [53], consistent with approaches used in previous studies [54-57]. These deprivation indices are based on data aggregated at the dissemination area level, which represents the smallest spatial unit available from census data in 2006 (in urban areas this is equivalent to an average of 400-700 individuals residing in one or more neighboring blocks of houses). They were constructed using a principal component analysis that integrated six census variables into two components (material and social). The material deprivation index is computed based on the proportion of individuals without a high-school diploma, their average personal earnings, and the employment-population ratio at the dissemination area level. The social deprivation index is computed from the proportions of individuals respectively living alone, heading a single-parent family, and being separated, divorced or widowed. Both material

and social deprivation indices were categorized into quintiles of equal population size, ranging from the most privileged (1st quintile) to the most deprived (5th quintile). We linked the children's 6-digit postal code data with the corresponding dissemination area which allowed us to identify participants' socioeconomic characteristics based on their neighborhood area.

Statistical Analyses

Analyses were conducted using SPSS (version 27). First, we examined the sample characteristics using means or frequencies. Second, we examined the association between greenspace and mental health problems using linear regression for continuous outcomes and logistic regression for suicidal ideation adjusting for identified individual, family and neighborhood characteristics. Associations were expressed in relation to one interquartile range (IQR) increase in the 250m buffer of childhood residential greenspace. The IQR for the childhood residential greenspace metric (maximum of surrounding annual mean NDVI values within a 250m buffer) was 0.15. Mental health problems outcomes were standardized (mean, 0; SD, 1) so that the regression coefficient (β) represents the standard deviation (SD) increase in symptoms associated with each IQR increase in greenspace. Third, to test whether sex and/or SES moderated the associations between greenspace exposure and mental health problems, interaction terms for these variables were examined separately in the fully adjusted models. Statistical significance was set at $p<.05$ and all tests were two-tailed.

Results

Sample Characteristics

Of the 2120 participants recruited at baseline, 1526 children participated in data collection in 2006 or 2008 and provided information on their postal code; of which 959 were living in urban regions. Of these, 742 participants (77.3%) provided information pertaining to

mental health problems (**Figure 1**). Key characteristics of the 742 participants are shown in **Table 1**. Participants residing in urban areas but who were not included in the study sample (n= 235) were more likely to be male (131/235 [55.7%] for those excluded from analyses vs. 336/742 [45.2%] for those included in analyses, c^2= 7.83, *p*=0.005); their mothers had more depressive symptoms at birth (1.52 vs. 1.30 [on a scale from 0 to 10], t_{971}= 2.23, *p*=0.026); and their parents had lower socioeconomic status at 5 months (z-scores -0.22 vs. 0.07, t_{970}= -3.95, *p*<0.001; **Supplement Table S4**).

Associations of Childhood Greenspace with Mental Health Problems and Moderations by Sex and Family SES

In the unadjusted model, an interquartile range increase in childhood greenspace exposure (0.15; 250m buffer) was associated with 0.14 SD decrease in adolescent inattention (β=-0.144,SE=0.055, *p*<0.01). This association persisted in the fully adjusted model with control for individual, family, and neighborhood characteristics, wherein an interquartile range increase in childhood greenspace exposure (0.15; 250m buffer) was associated with 0.13 SD decrease in adolescent inattention (β=-0.126,SE=0.059, *p*=0.032; **Figure 2A; Supplement Table S5)**. To verify the robustness of the results, sensitivity analyses were conducted to examine the 1) extent to which prescribed adolescent Ritalin use at 15/17 years of age may impact the association between greenspace exposure and ADHD and 2) whether or not important variations in the strength of association between greenspace exposure and mental health varies across different distance buffers (500m and 1000m). First, additional adjustment for adolescent past-year use of Ritalin (13.2% of sample) did not attenuate the association between childhood greenspace exposure and inattention (β=-0.128,SE=0.060,*p*=0.032). Second, similar pattern of results were observed across the three buffers for the association between greenspace exposure and inattention (see **Supplement Tables S6 and S7**).

No significant associations between childhood greenspace exposure and externalizing (conduct;β=-0.021,SE=0.058,*p*=0.715, hyperactivity/impulsivity; β=-0.044,SE=0.058,*p*=0.447,) and internalizing (depression; β=0.021, SE=0.055,*p*=0.704, anxiety;β=-0.017,SE=0.056,*p*=0.761, and suicidal ideation;Odds Ratio[OR]=1.25, 95%CI[0.83,1.89]); **Figure 2B-F; Supplement Table S5**) mental health problems were observed in adolescence, for both sexes combined.

Overall, associations between greenspace exposure and mental health problems were not moderated by child's sex (*p*s>0.05), except for a significant greenspace-by-sex interaction for conduct problems (β=-0.167,SE=0.075,*p*=0.025) at the 250m buffer, suggesting associations between higher greenspace and lower conduct problems in female (β=-0.130,SE=0.076, *p*=0.088) but not male (β =0.107,SE=0.082, *p*=0.193) participants. However, this greenspace-by-sex interaction for conduct problems was not replicated at the 500m and 1000m buffers (**Supplement Tables S6 and S7**). There were no significant interactions between childhood greenspace exposure and SES for any mental health problems (*p*s>0.05).

Discussion

This study examined associations between childhood urban greenspace exposure and a range of adolescent mental health problems in adolescence. After adjustment for characteristics at the individual, family, and neighborhood levels, including prior childhood mental health problems and socioeconomic characteristics, we found an association between greenspace exposure and reduced inattention problems in both males and females. We found no evidence of an association between greenspace exposure and adolescent hyperactivity/impulsivity, conduct, depression, anxiety, and suicidal ideation problems, and sex and family SES did not consistently moderate any of the associations.

Greenspace and ADHD

Our findings showing associations between childhood greenspace and lower inattention problems are in line with current knowledge summarized in systematic reviews [58, 59] including a few longitudinal studies [13, 14, 60, 61]. Consistent with the findings from our study, two longitudinal studies based on prospective cohorts from Germany and Denmark [14, 60] showed that increasing levels of residential greenspace were associated with fewer symptoms of ADHD throughout childhood and adolescence in both females and males. Moreover, in another sample of 57,450 New Zealand youth followed from ages 2 to 18 years, those exposed to increasing levels of neighborhood greenspace throughout their lives had a lower incidence of being diagnosed with ADHD before 18 years of age [13]. Conversely, in a sample of youth from England, increasing levels of residential greenspace was associated with lower levels of inattention, although these associations were better explained by socioeconomic status [61].

To the best of our knowledge, our study was the first to examine the strength of associations for the full spectrum of ADHD specific problems (inattention vs hyperactivity/impulsivity) which builds on prior research by showing that childhood greenspace exposure was associated with lower levels of inattention in females and males, but not hyperactivity-impulsivity problems. There are brain mechanism differences demonstrated in youth presenting with profiles of combined ADHD vs profiles of inattentive or hyperactive-impulsive problems only [62]. In the present study, the potential restorative qualities of greenspace exposure were observed for inattention problems across a variety of buffer zones (250m, 500m, 1000m). These results are in line with one robust randomized control study which demonstrated that youth diagnosed with ADHD (n=17) had better attention (assessed with the Digit Span Backwards, a standardized measure of concentration) after walking in a park, in

comparison to when they walked in an urban neighborhood, and the benefits of walking in a park in improving attention was large (Cohen's *d*= 0.77) [63]. These results echo those from a large observational study of children (7-10 years of age) residing in Spain that illustrated how over a 12-month period, children residing in the greenest neighborhoods improved their attentional capacities assessed via a computerized attentional task [29].

Greenspace and Other Mental Health Problems

Our study showed no significant associations between childhood greenspace exposure and depression and anxiety in adolescence. These results are consistent with another longitudinal study of American adolescents that indicated that childhood greenspace exposure was not associated with self-reported symptoms of anxiety and depression in adolescence [64]. Conversely, other longitudinal studies have shown that increased childhood greenspace exposure was associated with fewer symptoms of depression [65] and anxiety [12] in adolescence, although these studies used other greenspace metrics than NDVI as was utilized in our study. It has been illustrated that different greenspace metrics yield differing associations between greenspace exposure and mental health outcomes [66, 67].

Our finding that childhood greenspace was not associated with suicidal ideation in adolescence is in line with a previous study that evaluated associations between school surrounding greenspace and suicidal ideation in youth [33]. However, other studies based on adult populations [30, 31] have demonstrated that increased level of residential greenspace is linked to decreased risk of suicide mortality. It may be that greenspace exposure affects suicidal ideation and suicide mortality differently.

For conduct problems, our findings suggesting reduced symptoms among females (not males) exposed to higher levels of greenspace at the 250m buffer should be interpretated with

caution, as this result was not replicated within the 500m and 1000m buffer zones. Additionally, longitudinal studies have yielded mixed results [16, 26, 28]. On the one hand, a study of 1287 American adolescents indicated that more residential greenspace was associated with fewer aggressive symptoms in late adolescence [26]. On the other hand, a study of 715 Dutch adolescents reported no significant associations between surrounding residential greenspace and conduct problems when adolescents reached young adulthood [16]. In contrast to our findings that higher levels of surrounding greenspace were associated with fewer conduct problems in females, a study of 2909 Scottish children indicated that closer proximity to parks was associated with fewer conduct symptoms in boys, but not girls [28]. However, this study measured greenspace in terms of the proximity to parks, rather than the level of surrounding residential greenspace, as measured in our study.

Socioeconomic Inequalities in the Distribution of Greenspace

In line with studies from other countries, our results revealed socioeconomic inequalities in the distribution of greenspace, with children growing up in socioeconomically disadvantaged families being more likely to live in areas with lower levels of greenspace. Nevertheless, we did not find that greenspace was more beneficial for mental health problems of the most socioeconomically disadvantaged youth, as shown elsewhere [13, 14, 27].

Potential Mechanisms

Greenspace exposure may protect youth's mental health due to three major reasons. First, increased greenspace can reduce stress (e.g., cortisol) and increase attention, self-control, and problem-solving capacities, ultimately promoting the restoration of psychological well-being [68]. The "Attention Restoration Theory" posits that natural green environments diminish mental fatigue thus increasing attentional capacities [69]. Second, urban environments are notorious for

emitting air and noise pollutants which can have adverse consequences for mental health [70, 71]. Increased greenspace in urban settings provides the potential to mitigate major pollutants, as natural environments are not generally pollutant emission sites. Third, contact with greenspace strengthens psychosocial adaptation by encouraging physical activity and social connection, both of which are protective factors for mental health [72, 73].

Methodological Considerations

This study has several strengths, including its prospective design with greenspace exposure assessed in childhood and a wide range of mental health outcomes in adolescence. The use of a well-characterized cohort permitted the inclusion of several confounding factors at differing levels, including adjustment for prior mental health problems assessed in childhood. We also evaluated our associations between mental health and greenspace exposure across three circular buffer zones (250m, 500m, 1000m). However, some limitations should also be highlighted. First, although NDVI objectively quantifies the level of surrounding greenspace in a given area, it does not capture the quality, access, and use of greenspace, which has been previously associated with improved mental health in youth [74, 75]. Additionally, the present study examined residential greenspace only, while other greenspace exposure contexts, such as the school environment, may also impact mental health [33]. Second, surrounding greenspace was estimated at one time point in childhood and did not allow for an evaluation of the cumulative effects of greenspace exposure throughout childhood which may have underestimated the total greenspace exposure for a given participant over time [76, 77]. Future studies could examine the extent to which change in greenspace exposure overtime is associated with change in mental health symptom severity. Third, mental health problems were self-reported by adolescents which does not provide a clinical diagnosis for mental health problems,

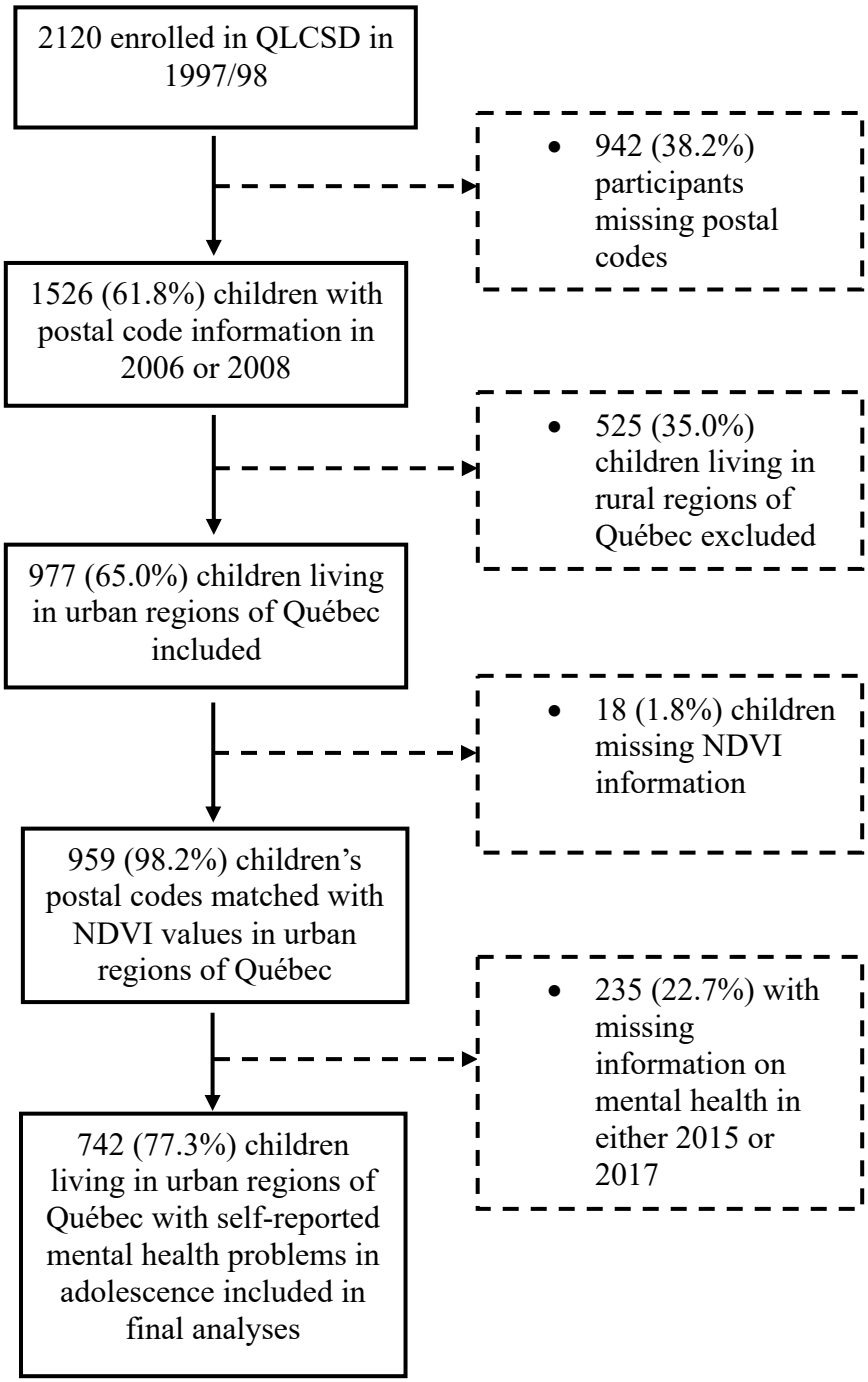
although the measure used [39] does cover the a large spectrum of mental health symptoms based on DSM-5 criteria. Fourth, the presence of potential unmeasured confounding factors is a limitation of this work, although we did adjust our analyses for individual, family, and neighborhood characteristics, consistent with previous studies [61, 78] and extending prior knowledge by adjusting for childhood mental health problems and parental depressive symptoms and antisocial behaviors. Of note, ethnicity and racism have been shown to intersect with environmental exposures and health [79], but there was insufficient data on these factors to adequately adjust for them in the QLSCD. Fifth, while psychometric properties are acceptable, the internal consistency for inattention problems (15 years α=0.66, 17 years α=0.68) was close but below the conventional 0.70 threshold [80], suggesting that these results may need to be interpreted cautiously. While the present study did not find differences in the associations by sex, future studies could examine if sex/gender potentially modify associations between greenspace exposure and mental health. Sixth, attrition occurred among potentially at-risk individuals, such as those from lower SES backgrounds, children of mothers with more depressive symptoms at birth, and male participants; which may have resulted in a selection bias and an underestimation of associations for these individuals.

Conclusion

Our longitudinal study revealed that higher levels of urban residential greenspace was associated with lower levels of inattention problems in male and female youth from all socioeconomic backgrounds. This finding along with other studies [14, 60] further highlights the importance of promoting the development of urban greenspace infrastructures to protect youth mental health. Although more studies are needed to elucidate the pathways by which greenspace benefits attentional abilities in youth, results from this study underscore the importance of promoting urban greenspace such as parks, gardens, street trees, or private backyards. Nevertheless, urban planning decisions may also consider other aspects of greenspace such as quality, quantity, and accessibility, which are also known to bring health benefits [74, 75].

Tables & Figures

Figure 1. Flowchart of participants the QLSCD cohort used in the study.



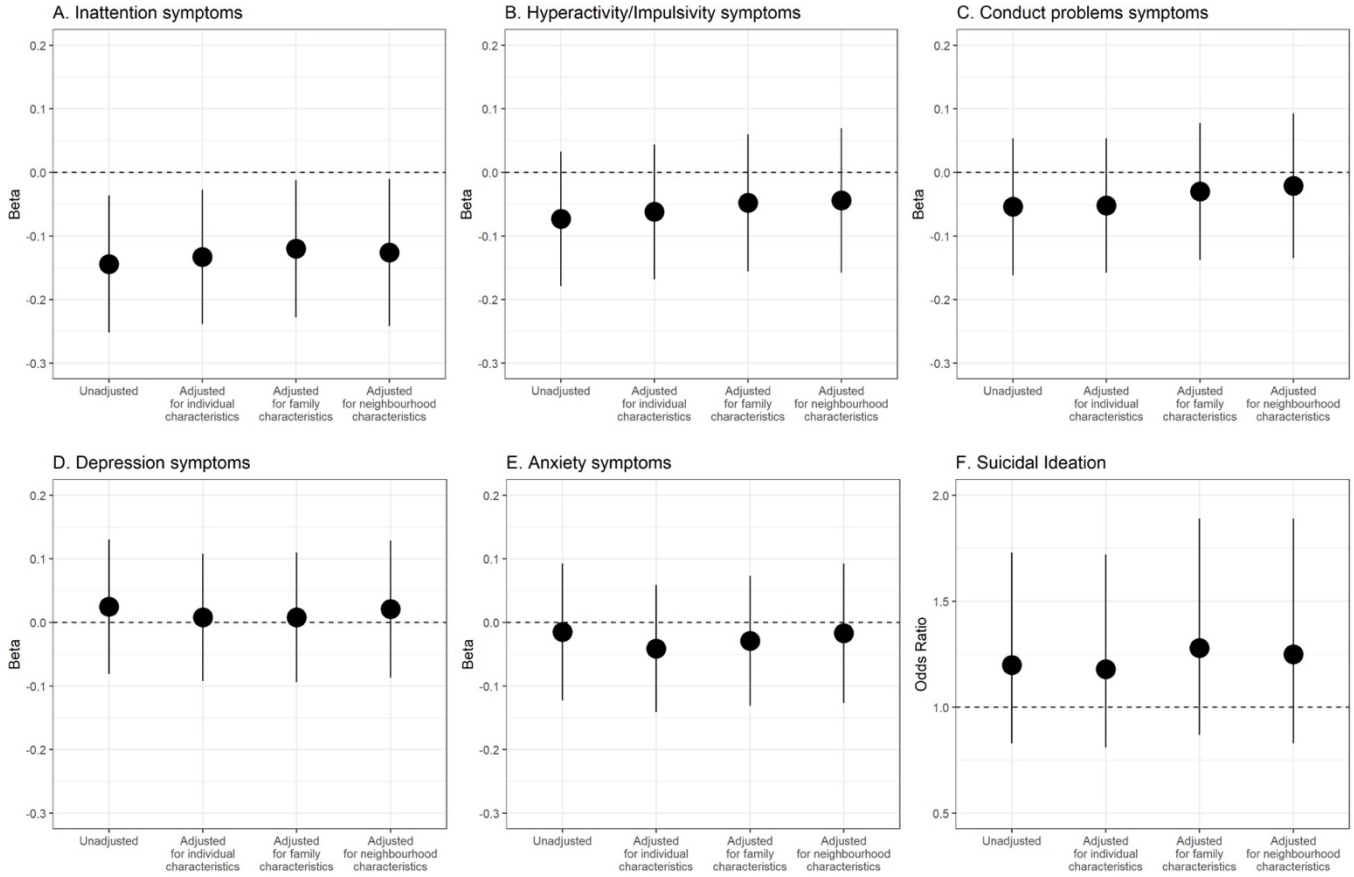
Note: Data were compiled from the final master file of the Québec Longitudinal Study of Child Development (1998–2017), ©Gouvernement du Québec, Institut de la statistique du Québec. Geographical region classification was calculated with Canadian census data in 2006 [81] based on all 6-digit postal codes in Québec which were then matched to the 6-digit postal codes of participants in the QLCSD. Participants residing in rural regions of Québec (i.e., regions with 10 000 to 100 000 residents) accounted for 35.0% of the cohort and were excluded from this study. QLSCD= Québec Longitudinal Study of Child Development.

Table 1. Key characteristics of 742 participants from the QLSCD surveyed at ages 15 to 17 years in 2013 or 2015 and greenspace exposure at age 10 years in 2006 and 2008[a,b]

	Study Sample	
Variables	M(SD)	N(%)
Adolescent mental health problems		
Conduct problems	0.74(0.86)	
Inattention	3.37(1.81)	
Hyperactivity/Impulsivity	2.61(1.57)	
Depression	3.62(2.01)	
Anxiety	4.31(1.97)	
Suicidal ideation		
Yes		73(9.8)
No		669(90.2)
Childhood NDVI (250m)	3.24(0.66)	
Individual-level		
Female		406(54.7)
Male		336(45.3)
Childhood conduct problems	1.53(0.77)	
Childhood ADHD	2.67(2.39)	
Childhood depression/anxiety	2.12(1.96)	
Adolescent Ritalin use[c]		
Yes		95(13.2)
No		627(86.8)
Family-level		
Maternal age	30.19(4.94)	
Parental depression	1.18(0.91)	
Parental antisociality		
Parental socioeconomic status	0.20(0.96)	
Family composition	0.41(0.54)	
Intact		521(70.2)
Not intact		221(29.8)
Neighborhood-level		
Material deprivation[c]		
Most privileged		253(34.1)
Most deprived		74(10.0)
Social deprivation[d]		
Most privileged		191(25.7)
Most deprived		108(14.6)

Note: Data are n(%) or mean (SD). NDVI= Normalized Difference Vegetation Index
Note: The Mental Health and Social Inadaptation Scale (Côté et al., 2017) was used to assess mental health problems, however these measures did not provide clinical diagnoses, but rather assessed severity of symptoms.
[a]Data were compiled from the final master file of the Québec Longitudinal Study of Child Development (1998–2017), ©Gouvernement du Québec, Institut de la statistique du Québec.
[b]NDVI metrics, indexed to DMTI Spatial Inc. postal codes, were provided by CANUE (Canadian Urban Environmental Health Research Consortium).
[c]Maximum available data was N=722
[d]Only data in the extreme categories are reported (1st quintile= most privileged; 5th quintile= most deprived)

Figure 2. Associations between residential greenspace exposure (250m) at age 10 years with adolescent mental health problems at either 15 to 17 years among 742 participants from the QLSCD[a,b]



Note: Analyses for inattention, impulsivity/hyperactivity, conduct, depression, anxiety, and suicidal ideation problems were conducted on the full sample as there was non-significant greenspace-by-sex interactions (*p*s > 0.05). Across all mental health problems, there were no significant greenspace-by-SES interactions (*p*s>0.05).
Note: Individual characteristics included sex and childhood mental health problems. Family characteristics included maternal age, parental mental health, socioeconomic status, and family composition. Neighborhood characteristics included material and social deprivation [53].
[a]Data were compiled from the final master file of the Québec Longitudinal Study of Child Development (1998–2017), ©Gouvernement du Québec, Institut de la statistique du Québec.
[b]NDVI metrics, indexed to DMTI Spatial Inc. postal codes were provided by CANUE (Canadian Urban Environmental Health Research Consortium).

References

1. Mental Health Commission of Canada. *Mental Health Commission of Canada Youth Council* 2022; Available from: https://commissionsantementale.ca/a-propos-de-nous/groupes-de-la-commission/conseil-des-jeunes-de-la-csmc/.
2. Wiens, K., et al., *A growing need for youth mental health services in Canada: examining trends in youth mental health from 2011 to 2018.* Epidemiology and Psychiatric Sciences, 2020. **29**.
3. Taylor, L. and D.F. Hochuli, *Defining greenspace: Multiple uses across multiple disciplines.* Landscape and urban planning, 2017. **158**: p. 25-38.
4. Bratman, G.N., et al., *Nature and mental health: An ecosystem service perspective.* Science Advances, 2019. **5**(7): p. eaax0903.
5. Hartig, T., et al., *Nature and health.* Annual Review of Public Health, 2014. **35**: p. 207-228.
6. Bratman, G.N., J.P. Hamilton, and G.C. Daily, *The impacts of nature experience on human cognitive function and mental health.* Annals of the New York academy of sciences, 2012. **1249**(1): p. 118-136.
7. Browning, M.H., A. Rigolon, and O. McAnirlin, *Where greenspace matters most: A systematic review of urbanicity, greenspace, and physical health.* Landscape and Urban Planning, 2022. **217**: p. 104233.
8. Markevych, I., et al., *Exploring pathways linking greenspace to health: Theoretical and methodological guidance.* Environmental research, 2017. **158**: p. 301-317.
9. Rhew, I.C., et al., *Validation of the normalized difference vegetation index as a measure of neighborhood greenness.* Annals of Epidemiology, 2011. **21**(12): p. 946-952.

10. Bezold, C.P., et al., *The association between natural environments and depressive symptoms in adolescents living in the United States.* Journal of Adolescent Health, 2018. **62**(4): p. 488-495.

11. Engemann, K., et al., *Residential green space in childhood is associated with lower risk of psychiatric disorders from adolescence into adulthood.* Proceedings of the National Academy of Sciences, 2019. **116**(11): p. 5188-5193.

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

13. Donovan, G.H., et al., *Association between exposure to the natural environment, rurality, and attention-deficit hyperactivity disorder in children in New Zealand: a linkage study.* The Lancet Planetary Health, 2019. **3**(5): p. e226-e234.

14. Thygesen, M., et al., *The association between residential green space in childhood and development of attention deficit hyperactivity disorder: a population-based cohort study.* Environmental Health Perspectives, 2020. **128**(12): p. 127011.

15. Maes, M.J., et al., *Benefit of woodland and other natural environments for adolescents' cognition and mental health.* Nature Sustainability, 2021. **4**(10): p. 851-858.

16. Weeland, J., et al., *The greener the better? Does neighborhood greenness buffer the effects of stressful life events on externalizing behavior in late adolescence?* Health & place, 2019. **58**: p. 102163.

17. Jimenez, M.P., et al., *Early life exposure to greenness and executive function and behavior: An application of inverse probability weighting of marginal structural models.* Environmental Pollution, 2021. **291**: p. 118208.

18. Astell-Burt, T., R. Mitchell, and T. Hartig, *The association between green space and mental health varies across the lifecourse. A longitudinal study.* Epidemiol Community Health, 2014. **68**(6): p. 578-583.

19. Feng, X. and T. Astell-Burt, *Residential green space quantity and quality and child well-being: a longitudinal study.* American Journal of Preventive Medicine, 2017. **53**(5): p. 616-624.

20. Sillman, D., et al., *Do sex and gender modify the association between green space and physical health? A systematic review.* Environmental Research, 2022. **209**: p. 112869.

21. Bolte, G., S. Nanninga, and L. Dandolo, *Sex/gender differences in the association between residential green space and self-rated health—A sex/gender-focused systematic review.* International journal of environmental research and public health, 2019. **16**(23): p. 4818.

22. Mitchell, R. and F. Popham, *Effect of exposure to natural environment on health inequalities: an observational population study.* The lancet, 2008. **372**(9650): p. 1655-1660.

23. Hartig, T., *Green space, psychological restoration, and health inequality.* The Lancet, 2008.

24. Mitchell, R.J., et al., *Neighborhood environments and socioeconomic inequalities in mental well-being.* American Journal of Preventive Medicine, 2015. **49**(1): p. 80-84.

25. Wheeler, B.W., et al., *Beyond greenspace: an ecological study of population general health and indicators of natural environment type and quality.* International Journal of Health Geographics, 2015. **14**(1): p. 1-17.

26. Younan, D., et al., *Environmental determinants of aggression in adolescents: Role of urban neighborhood greenspace.* Journal of the American Academy of Child Adolescent Psychiatry, 2016. **55**(7): p. 591-601.

27. Flouri, E., E. Midouhas, and H. Joshi, *The role of urban neighbourhood green space in children's emotional and behavioural resilience.* Journal of Environmental Psychology, 2014. **40**: p. 179-186.

28. Richardson, E.A., et al., *The role of public and private natural space in children's social, emotional and behavioural development in Scotland: A longitudinal study.* Environmental research, 2017. **158**: p. 729-736.

29. Dadvand, P., et al., *Green spaces and cognitive development in primary schoolchildren.* Proceedings of the National Academy of Sciences, 2015. **112**(26): p. 7937-7942.

30. Shen, Y.-S. and S.-C.C. Lung, *Identifying critical green structure characteristics for reducing the suicide rate.* Urban Forestry Urban Greening, 2018. **34**: p. 147-153.

31. Helbich, M., et al., *Natural environments and suicide mortality in the Netherlands: a cross-sectional, ecological study.* The Lancet Planetary Health, 2018. **2**(3): p. e134-e139.

32. Min, K.-b., et al., *Parks and green areas and the risk for depression and suicidal indicators.* International Journal of Public Health, 2017. **62**(6): p. 647-656.

33. Srugo, S.A., et al., *Assessing the impact of school-based greenness on mental health among adolescent students in Ontario, Canada.* International Journal of Environmental Research Public Health, 2019. **16**(22): p. 4364.

34. Orri, M., et al., *Cohort profile: Québec longitudinal study of child development (QLSCD).* Social Psychiatry and Psychiatric Epidemiology, 2021. **56**: p. 883-894.

35. Jetté M, *Survey Description and Methodology" in Longitudinal Study of Child Development in Québec (ÉLDEQ 1998–2002).* Inst Stat Qué 1, 2000.

36. Haggerty, J.L., et al., *An exploration of rural–urban differences in healthcare-seeking trajectories: Implications for measures of accessibility.* Health Place, 2014. **28**: p. 92-98.

37. Fleet, R., et al., *Portrait of rural emergency departments in Québec and utilization of the provincial emergency department management Guide: cross sectional survey.* BMC Health Services Research, 2015. **15**(1): p. 572.

38. Engemann, K., et al., *Childhood exposure to green space–A novel risk-decreasing mechanism for schizophrenia?* Schizophrenia Research, 2018. **199**: p. 142-148.

39. Côté, S.M., et al., *Psychometric properties of the Mental Health and Social Inadaptation Assessment for Adolescents (MIA) in a population-based sample.* International Journal of Methods in Psychiatric Research, 2017. **26**(4): p. e1566.

40. James, P., et al., *A review of the health benefits of greenness.* Current Epidemiology Reports, 2015. **2**(2): p. 131-142.

41. Gorelick, N., et al., *Google Earth Engine: Planetary-scale geospatial analysis for everyone.* Remote Sensing of Environment, 2017. **202**: p. 18-27.

42. *USGS Landsat 5 TM TOA Reflectance (Orthorectified), 1984 to 2011*. [cited 2017 July]; Available from: https://explorer.earthengine.google.com/#detail/LANDSAT%2FLT5_L1T_TOA.

43. *Landsat 5 TM Annual Greenest-Pixel TOA Reflectance Composite, 1984 to 2012*. [cited 2017 July]; Available from: https://explorer.earthengine.google.com/#detail/LANDSAT%2FLT5_L1T_ANNUAL_GREENEST_TOA.

44. DMTI Spatial Inc, *CanMap Postal Code Suite v2015.3. [Computer file]*. 2015, DMTI Spatial Inc: Markham, ON, Canada, 2015.

45. Rosu, A. and D. Chen, *An improved approach for geocoding Canadian postal code–based data in health-related studies.* The Canadian Geographer/Le Géographe canadien, 2016. **60**(2): p. 270-281.

46. Hystad, P., et al., *Green space associations with mental health and cognitive function: Results from the Québec CARTaGENE cohort.* Environmental Epidemiology, 2019. **3**(1): p. e040.

47. Collet, O.A., et al., *Psychometric properties of the Social Behavior Questionnaire (SBQ) in a longitudinal population-based sample.* International Journal of Behavioral Development, 2022: p. 01650254221113472.

48. Children, N.L.S.o., *Overview of Survey Instruments for 1994-95 Data Collection Cycle 1*. 1995: Statistics Canada; Hull, Québec: Human Resources Development Canada.

49. Achenbach, T.M., C. Edelbrock, and C.T. Howell, *Empirically based assessment of the behavioral/emotional problems of 2-and 3-year-old children.* Journal of abnormal child psychology, 1987. **15**(4): p. 629-650.

50. Lewinsohn, P.M., et al., *Center for Epidemiologic Studies Depression Scale (CES-D) as a screening instrument for depression among community-residing older adults.* Psychology Aging, 1997. **12**(2): p. 277.

51. Zoccolillo, M., *Parents' health and social adjustment: part II, social adjustment.* Longitudinal study of child development in Québec, 2000: p. 37-45.

52. Willms, D. and M. Shields, *A measure of socioeconomic status for the National Longitudinal Study of Children*. Vol. 9607. 1996, Fredericton, New Brunswick: Atlantic Center for Policy Research in Education, University of New Brunswick and Statistics

53. Pampalon, R. and G. Raymond, *A deprivation index for health and welfare planning in Québec.* Chronic Diseases in Canada, 2000. **21**(3): p. 104-113.

54. Gariepy, G., et al., *Place and health in diabetes: the neighbourhood environment and risk of depression in adults with Type 2 diabetes.* Diabetic Medicine, 2015. **32**(7): p. 944-950.

55. Schmitz, N., et al., *Association between neighborhood-level deprivation and disability in a community sample of people with diabetes.* Diabetes Care, 2009. **32**(11): p. 1998-2004.

56. Short, H., et al., *The relationship of neighbourhood-level material and social deprivation with health-related quality of life.* Quality of Life Research, 2018. **27**(12): p. 3265-3274.

57. Philibert, M.D., et al., *Interactions between neighborhood characteristics and individual functional status in relation to disability among Québec urbanites.* Disability Health Journal, 2013. **6**(4): p. 361-368.

58. Fyfe-Johnson, A.L., et al., *Nature and Children's Health: A Systematic Review.* Pediatrics, 2021. **148**(4).

59. Sakhvidi, M.J.Z., et al., *Greenspace exposure and children behavior: A systematic review.* Science of the Total Environment, 2022: p. 153608.

60. Markevych, I., et al., *Outdoor air pollution, greenspace, and incidence of ADHD: A semi-individual study.* Sci Total Environ, 2018. **642**: p. 1362-1368.

61. Reuben, A., et al., *Residential neighborhood greenery and children's cognitive development.* Social Science Medicine, 2019. **230**: p. 271-279.

62. Saad, J.F., K.R. Griffiths, and M.S. Korgaonkar, *A systematic review of imaging studies in the combined and inattentive subtypes of attention deficit hyperactivity disorder.* Frontiers in Integrative Neuroscience, 2020. **14**: p. 31.

63. Faber Taylor, A. and F.E. Kuo, *Children with attention deficits concentrate better after walk in the park.* Journal of Attention Disorders, 2009. **12**(5): p. 402-409.

64. Hartley, K., et al., *Residential surrounding greenness and self-reported symptoms of anxiety and depression in adolescents.* Environmental Research, 2021. **194**: p. 110628.

65. Bezold, C.P., et al., *The relationship between surrounding greenness in childhood and adolescence and depressive symptoms in adolescence and early adulthood.* Annals of Epidemiology, 2018. **28**(4): p. 213-219.

66. Jarvis, I., et al., *Greenspace access does not correspond to nature exposure: Measures of urban natural space with implications for health research.* Landscape and Urban Planning, 2020. **194**: p. 103686.

67. Larkin, A. and P. Hystad, *Evaluating street view exposure measures of visible green space for health research.* Journal of exposure science & environmental epidemiology, 2019. **29**(4): p. 447-456.

68. Bratman, G.N., et al., *Nature and mental health: An ecosystem service perspective.* Science Advances, 2019. **5**(7): p. eaax0903.

69. Kaplan, S., *The restorative benefits of nature: Toward an integrative framework.* Journal of environmental psychology, 1995. **15**(3): p. 169-182.

70. Latham, R.M., et al., *Childhood exposure to ambient air pollution and predicting individual risk of depression onset in UK adolescents.* Journal of Psychiatric Research, 2021. **138**: p. 60-67.

71. Klompmaker, J.O., et al., *Associations of combined exposures to surrounding green, air pollution and traffic noise on mental health.* Environment International, 2019. **129**: p. 525-537.

72. De Vries, S., et al., *Streetscape greenery and health: stress, social cohesion and physical activity as mediators.* Social Science Medicine, 2013. **94**: p. 26-33.

73. Richardson, E.A., et al., *Role of physical activity in the relationship between urban green space and health.* Public Health, 2013. **127**(4): p. 318-324.

74. McCormick, R., *Does access to green space impact the mental well-being of children: A systematic review.* Journal of Pediatric Nursing, 2017. **37**: p. 3-7.

75. Zhang, Y., et al., *The association between green space and adolescents' mental well-being: a systematic review.* International Journal of Environmental Research Public Health, 2020. **17**(18): p. 6640.

76. Brokamp, C., G.K. LeMasters, and P.H. Ryan, *Residential mobility impacts exposure assessment and community socioeconomic characteristics in longitudinal epidemiology studies.* Journal of Exposure Science Environmental Epidemiology, 2016. **26**(4): p. 428-434.

77. Clark, W., M. Deurloo, and F. Dieleman, *Residential mobility and neighbourhood outcomes.* Housing Studies, 2006. **21**(3): p. 323-342.

78. Mavoa, S., et al., *Natural neighbourhood environments and the emotional health of urban New Zealand adolescents.* Landscape Urban Planning, 2019. **191**: p. 103638.

79. Abi Deivanayagam, T., et al., *Envisioning environmental equity: climate change, health, and racial justice.* The Lancet, 2023.

80. Tavakol, M. and R. Dennick, *Making sense of Cronbach's alpha.* International journal of medical education, 2011. **2**: p. 53.

81. *Institut national de santé publique du Québec (INSPQ) à partir des données des recensements canadiens de 1991, 1996, 2001, 2006, 2011 et 2016. Indice de défavorisation matérielle et sociale compilé par le Bureau d'information et d'études en santé des populations (BIESP)*. Available from: https://www.inspq.qc.ca/expertises/gestion-et-analyse-de-l-information/diffusion-d-une-information-adaptee/santescope/indice-de-defavorisation.

Supplementary Tables

Table S1. Mental Health and Social Inadaptation Assessment for Adolescents item subscales

Table S2. Correlation coefficients between mental health problems reported at 15 and 17 years among 742 participants from the QLSCD

Table S3. Correlation coefficients between residential greenspace exposure at age 10 years, mental health problems at 15 and 17 years, and potential confounding factors among 742 participants from the QLSCD

Table S4. Comparisons of participants included and excluded from analysis based on key variables

Table S5. Associations of residential greenspace exposure (250m) at age 10 years with mental health problems at 15 and 17 years among 742 participants from the QLSCD

Table S6. Associations of residential greenspace exposure (500m) at age 10 years with mental health problems at 15 and 17 years among 742 participants from the QLSCD

Table S7. Associations of residential greenspace exposure (1000m) at age 10 years with mental health problems at 15 and 17 years among 742 participants from the QLSCD

Table S1. Mental Health and Social Inadaptation Assessment for Adolescents item subscales

Mental Health Problems	Items
Depression 15 (α = 0.83) and 17 (α = 0.88) years	a. Nothing was fun for me, I wasn't interested in anything. b. I felt sad and unhappy. c. I lacked energy or felt tired. d. I lost interest in things I usually like. e. I felt I couldn't do anything well. f. I felt I wasn't as good-looking or as smart as other people. g. Doing even little things made me feel really tired. h. I had trouble thinking clearly.
Anxiety 15 (α = 0.80) and 17 (α = 0.80) years	a. I was too fearful or nervous. b. I had worries that interfered with my everyday life. c. I worried about my past behaviour. d. I worried about my school work. e. I worried about my own health. f. I worried about my loved ones (family, friends). g. I worried about my relationships with my friends (i.e. making and keeping friends). h. I was concerned about my appearance or weight. i. I found it difficult to control the worry.
Conduct 15 (α = 0.83) and 17 (α = 0.93) years	a. I cheated in order to succeed at school. b. I cheated in order to make some money. c. I cheated in order to win a competition. d. I told lies in order to get things or favours from others. e. I told lies in order to get out of doing things I was supposed to do. f. I stole money or objects from home. g. I stole money or objects from school or from stores. h. I used a weapon in order to steal. i. I entered a house, a building or a car without permission in order to steal.

	j. I broke down a door or a window in order to get into a place and take something. k. I stayed out at night much later than I was allowed to. l. I stayed out all night without my parents' permission. m. I ran away from home. n. I skipped school without reason (cut class). o. I deliberately started a fire. p. I deliberately destroyed someone else's property.
Inattention 15 (α = 0.66) and 17 () years	a. I was inattentive, I had difficulty paying attention to what someone was saying or doing. b. I completed all of my tasks or homework, I was able to stay focused. (reverse coding) c. I had trouble keeping my mind on what I was doing for more than a few minutes. d. I forgot what I was supposed to be doing or what I had planned to do. e. I avoided doing things where I needed to pay attention for a long time. f. I made a lot of mistakes because it was hard for me to do things carefully.
Hyperactivity/Impulsivity 15 (α = 0.78) and 17 (α = 0.87) years	a. I felt very restless, I was constantly on the move. b. I often stood up in class or in other situations where I was supposed to remain seated. c. I often had trouble staying calm during games or leisure activities. d. I moved my hands and feet, I wriggled in my chair. e. I was impulsive (reacted quickly without thinking). f. I said things before thinking them through. g. I did or said things without stopping to think. h. I had difficulty waiting for my turn in games or group activities. i. I often blurted out the answer to a question that hadn't yet been completely asked. j. I got into trouble because I did things without thinking.

Table S2. Correlation coefficients between mental health problems reported at 15 and 17 years among 742 participants from the QLSCD [a]

Mental health problems 15 years	**Mental health problems 17 years**					
	Inattention	Hyperactivity/Impulsivity	Conduct	Depression	Anxiety	Suicidal Ideation
Inattention	**0.52****	-	-	-	-	
Hyperactivity/Impulsivity	**-**	**0.51****				
Conduct	-	**-**	**0.54****	-	-	
Depression	-	-	-	**0.59****	-	
Anxiety	-	-	-	-	**0.61****	
Suicidal ideation[b]	-	-	-	-	-	**0.52****

Note: All significant correlations are bolded. * p <0 .05. **p <0.01.

Note: Pearson coefficients (r) were calculated for continuous mental health problems variables (ADHD, conduct, depression, anxiety).

[a]Data were compiled from the final master file of the Québec Longitudinal Study of Child Development (1998–2017), ©Gouvernement du Québec, Institut de la statistique du Québec.

[b] Spearman coefficient (r_s) was calculated for categorical variable.

Table S3. Correlation coefficients between residential greenspace exposure at age 10 years, mental health problems at 15 and 17 years, and potential confounding factors among 742 participants from the QLSCD[a,b]

		Exposure and Mental Health Problems[c]					
Confounding Factors	Childhood NDVI	Inattention	Hyperactivity/ Impulsivity	Conduct Problems	Depression	Anxiety	Suicidal ideation
Individual level							
Childhood mental health problems[d,f]							
Oppositional and defiant behaviours	0.06	0.06	**0.08***	**0.12****	-0.02	-0.02	0.06
ADHD	-0.05	**0.17****	**0.14****	**0.11****	-0.07	**-0.12****	0.04
Depressive and anxious symptoms	0.01	**0.09***	-0.00	-0.05	0.02	0.02	0.02
Adolescent Ritalin use	0.01	**0.17****	0.06	0.05	0.02	-0.01	**0.08***
Family level							
Parental SES[d,g]	**0.17****	-0.07	-0.06	-0.05	0.00	-0.01	-0.05
Maternal age at childbirth[d]	0.05	-0.01	-0.06	**-0.08***	-0.04	0.01	-0.04
Parental mental health							
Depression[d,h]	**-0.13****	0.05	0.07	**0.08***	0.01	0.04	**0.09***
Antisocial behaviours[d,i]	-0.02	**0.08***	**0.12****	**0.15****	0.04	-0.00	**-0.12****
Family composition[d,j]	**0.11****	**-0.10****	-0.05	**-0.09***	-0.03	-0.05	-0.06
Neighborhood level							
Material deprivation[e,k]	**-0.28****	0.05	0.03	0.07	0.00	0.03	-0.03
Social deprivation[e,l]	**-0.26****	0.06	0.04	-0.03	0.03	0.03	0.05

Note: All significant correlations are bolded. * $p < 0.05$. **$p < 0.01$.

[a]Data were compiled from the final master file of the Québec Longitudinal Study of Child Development (1998–2017), ©Gouvernement du Québec, Institut de la statistique du Québec.

[b]NDVI metrics, indexed to DMTI Spatial Inc. postal codes, were provided by CANUE (Canadian Urban Environmental Health Research Consortium).

[c]The Mental Health and Social Inadaptation Scale [1] was used to assess mental health problems, however these measures did not provide clinical diagnoses, but rather assessed severity of symptoms.

[d]Pearson coefficients (r) were calculated for continuous confounding factors.

[e]Spearman coefficients (r_s) were calculated for categorical confounding factors.

[f]Childhood mental health problems reported by school teachers derived from the Canadian National Longitudinal Study [2] and based on items from the Child Behaviour Checklist [3]

[g]Parental SES measured as standardized index based on annual gross income, parental education level and occupational prestige [4].

[h]Maternal and paternal depressive symptoms at 5 months were measured using a short form of the Centre for Epidemiological Study Depression Scale (12 items; e.g. "I felt depressed") [5]. Score range: 0–10.

[i]Maternal and paternal antisocial behavior during adolescence was assessed based on *DSM-IV* criteria for conduct disorder and personality disorder [6]. Score range: 0–5.

[j]Family composition categorized as intact and non-intact.

[k]Material deprivation represents the proportion of individuals without a high-school diploma, average personal income and the employment-population ratio [7]. Categorized into quintiles of equal population size, ranging from the most privileged (1st quintile) to the most deprived (5th quintile) [8].

[l]Social deprivation represents the proportion of individuals living alone, separated, divorced or widowed [7]. Categorized into quintiles of equal population size, ranging from the most privileged (1st quintile) to the most deprived (5th quintile) [8].

Table S4. Comparisons of participants included and excluded from analysis based on key variables[a]

	Included (n=742)	Excluded (n=235)	p-value
Male, No.(%)	336(45.2)	131(55.7)	0.005
Maternal age at birth in years, mean (SD)	30.19(4.94)	30.27(5.42)	0.852
Maternal depression, mean (SD)[b]	1.30(1.23)	1.52(1.46)	0.026
Non-intact family (single or blended), No.(%)	122(16.4)	47(20.0)	0.192
Family socioeconomic status at birth[c]	0.07(0.96)	-0.22(1.10)	<0.001

Note: Variables were measured when the child was 5 months of age.

[a] Data were compiled from the final master file of the Québec Longitudinal Study of Child Development (1998–2017), ©Gouvernement du Québec, Institut de la statistique du Québec.

[b] Measured using a short form of the Centre for Epidemiological Study Depression Scale (12 items; e.g. "I felt depressed") [5]. Score range: 0–10.·

[c] Z-scores reflecting a standardized index based on annual gross income, parental education level and occupational prestige [4]

Table S5. Associations of residential greenspace exposure (250m) at age 10 years with mental health problems at 15 and 17 years among 742 participants from the QLSCD [a,b]

	Unadjusted		Adjusted for individual characteristics		Additionally adjusted for family characteristics		Additionally adjusted for neighborhood characteristics	
	β (±*SE*)	*p*	β (±*SE*)	*p*	β (±*SE*)	*p*	β (±*SE*)	*p*
Inattention	**-0.144(±0.055)**	**0.009**	**-0.133(±0.054)**	**0.015**	**-0.120(±0.055)**	**0.031**	**-0.126(±0.059)**	**0.032**
Hyperactivity/Impulsivity	-0.073(±0.054)	0.180	-0.062(±0.054)	0.254	-0.048(±0.055)	0.388	-0.044(±0.058)	0.447
Conduct problems	-0.054(±0.055)	0.328	-0.052(±0.054)	0.340	-0.030(±0.055)	0.585	-0.021(±0.058)	0.715
Depression	0.025 (±0.054)	0.462	0.008 (±0.051)	0.872	0.008 (±0.052)	0.875	0.021 (±0.055)	0.704
Anxiety	-0.015 (±0.055)	0.791	-0.041 (±0.051)	0.426	-0.029 (±0.052)	0.584	-0.017 (±0.056)	0.761
	OR (95%CI)		OR (95%CI)		OR (95%CI)		OR (95%CI)	
Suicidal ideation[c]	1.20 (0.83, 1.73)		1.18 (0.81,1.72)		1.28 (0.87,1.89)		1.25 (0.83,1.89)	

Note: Individual characteristics included sex and childhood mental health problems. Family characteristics included maternal age, parental mental health, socioeconomic status, and family composition. Neighborhood characteristics included material and social deprivation [7].

The Mental Health and Social Inadaptation Scale [1] was used to assess mental health problems, however these measures did not provide clinical diagnoses, but rather assessed severity of symptoms.

There was no significant residential greenspace-by-sex interaction for inattention (p=0.093), hyperactivity/impulsivity (p=0.120), depression (p= 0.521), anxiety (p= 0.400), and suicidal ideation (p= *0.*981) therefore analyses were conducted on the total sample. Across all mental health problems, there were no significant greenspace-by-SES interactions (ps>0.05).

[a]Data were compiled from the final master file of the Québec Longitudinal Study of Child Development (1998–2017), ©Gouvernement du Québec, Institut de la statistique du Québec.

[b]NDVI metrics, indexed to DMTI Spatial Inc. postal codes were provided by CANUE (Canadian Urban Environmental Health Research Consortium).

[c]Suicidal ideation categorized as no versus yes. OR= Odds Ratios. 95%CI= 95% Confidence Interval.

Table S6. Associations of residential greenspace exposure (500m) at age 10 years with mental health problems at 15 and 17 years among 742 participants from the QLSCD [a,b]

	Unadjusted		Adjusted for individual characteristics		Additionally adjusted for family characteristics		Additionally adjusted for neighborhood characteristics	
	β (±*SE*)	*p*	β (±*SE*)	*p*	β (±*SE*)	*p*	β (±*SE*)	*p*
Inattention	**-0.166(±0.053)**	**0.002**	**-0.151(±0.052)**	**0.004**	**-0.137(±0.053)**	**0.011**	**-0.146(±0.057)**	**0.010**
Hyperactivity/Impulsivity	-0.087(±0.053)	0.098	-0.075(±0.052)	0.151	-0.064(±0.053)	0.225	-0.064(±0.056)	0.257
Conduct problems	-0.051(±0.053)	0.332	-0.049(±0.053)	0.352	-0.032(±0.053)	0.551	-0.023(±0.056)	0.687
Depression	-0.022 (±0.052)	0.674	-0.030(±0.049)	0.532	-0.031 (±0.050)	0.532	-0.024 (±0.053)	0.654
Anxiety	-0.078 (±0.054)	0.143	-0.096 (±0.050)	0.053	-0.086 (±0.051)	0.089	-0.082 (±0.54)	0.129
	OR (95%CI)		OR (95%CI)		OR (95%CI)		OR (95%CI)	
Suicidal ideation[c]	1.11 (0.77, 1.58)		1.11 (0.77,1.60)		1.18 (0.81,1.73)		1.14 (0.76,1.71)	

Note: Individual characteristics included sex and childhood mental health problems. Family characteristics included maternal age, parental mental health, socioeconomic status, and family composition. Neighborhood characteristics included material and social deprivation [7].

The Mental Health and Social Inadaptation Scale [1] was used to assess mental health problems, however these measures did not provide clinical diagnoses, but rather assessed severity of symptoms.

There was no significant residential greenspace-by-sex interaction for conduct (p=0.081), inattention (p=0.595), hyperactivity/impulsivity (p=0.992), depression (p=0.801), anxiety (p=0.331), and suicidal ideation (p=0.550) therefore analyses were conducted on the total sample. Across all mental health problems, there were no significant greenspace-by-SES interactions (ps>0.05).

[a]Data were compiled from the final master file of the Québec Longitudinal Study of Child Development (1998–2017), ©Gouvernement du Québec, Institut de la statistique du Québec.

[b]NDVI metrics, indexed to DMTI Spatial Inc. postal codes were provided by CANUE (Canadian Urban Environmental Health Research Consortium).

[c]Suicidal ideation categorized as no versus yes. OR= Odds Ratios. 95%CI= 95% Confidence Interval.

Table S7. Associations of residential greenspace exposure (1000m) at age 10 years with mental health problems at 15 and 17 years among 742 participants from the QLSCD [a,b]

	Unadjusted		Adjusted for individual characteristics		Additionally adjusted for family characteristics		Additionally adjusted for neighborhood characteristics	
	β (±*SE*)	*p*	β (±*SE*)	*p*	β (±*SE*)	*p*	β (±*SE*)	*p*
Inattention	**-0.152(±0.062)**	**0.014**	**-0.137(±0.061)**	**0.026**	**-0.119(0.062±)**	**0.057**	**-0.125(±0.066)**	**0.060**
Hyperactivity/Impulsivity	-0.091(±0.061)	0.136	-0.075(±0.061)	0.220	-0.066(±0.062)	0.285	-0.065(0.066±)	0.323
Conduct problems	-0.037(±0.062)	0.550	-0.029(±0.061)	0.637	-0.016(±0.062)	0.797	-0.002(±0.066)	0.980
Depression	0.017 (±0.061)	0.782	0.002 (±0.057)	0.971	0.002 (±0.058)	0.977	0.014 (±0.062)	0.816
Anxiety	-0.045 (±0.062)	0.467	-0.073 (±0.058)	0.210	-0.061 (±0.059)	0.300	-0.051 (±0.063)	0.417
	OR (95%CI)		OR (95%CI)		OR (95%CI)		OR (95%CI)	
Suicidal ideation[c]	1.09 (0.72, 1.66)		1.09 (0.71,1.67)		1.15 (0.75,1.78)		1.10 (0.69,1.77)	

Note: Individual characteristics included sex and childhood mental health problems. Family characteristics included maternal age, parental mental health, socioeconomic status, and family composition. Neighborhood characteristics included material and social deprivation [7].

The Mental Health and Social Inadaptation Scale [1] was used to assess mental health problems, however these measures did not provide clinical diagnoses, but rather assessed severity of symptoms.

There was no significant residential greenspace-by-sex interaction for conduct (p=0.078), inattention (p=0.092), hyperactivity/impulsivity (p=0.812), depression (p= 0.906), anxiety (p= 0.818), and suicidal ideation (p= 0.558) therefore analyses were conducted on the total sample. Across all mental health problems, there were no significant greenspace-by-SES interactions (ps>0.05).

[a]Data were compiled from the final master file of the Québec Longitudinal Study of Child Development (1998–2017), ©Gouvernement du Québec, Institut de la statistique du Québec.

[b]NDVI metrics, indexed to DMTI Spatial Inc. postal codes were provided by CANUE (Canadian Urban Environmental Health Research Consortium).

[c]Suicidal ideation categorized as no versus yes. OR= Odds Ratios. 95%CI= 95% Confidence Interval.

Supplement References

1. Côté, S.M., et al., *Psychometric properties of the Mental Health and Social Inadaptation Assessment for Adolescents (MIA) in a population-based sample.* International Journal of Methods in Psychiatric Research, 2017. **26**(4): p. e1566.
2. Children, N.L.S.o., *Overview of Survey Instruments for 1994-95 Data Collection Cycle 1*. 1995: Statistics Canada; Hull, Québec: Human Resources Development Canada.
3. Achenbach, T.M., C. Edelbrock, and C.T. Howell, *Empirically based assessment of the behavioral/emotional problems of 2-and 3-year-old children.* Journal of abnormal child psychology, 1987. **15**(4): p. 629-650.
4. Willms, D. and M. Shields, *A measure of socioeconomic status for the National Longitudinal Study of Children*. Vol. 9607. 1996, Fredericton, New Brunswick: Atlantic Center for Policy Research in Education, University of New Brunswick and Statistics
5. Lewinsohn, P.M., et al., *Center for Epidemiologic Studies Depression Scale (CES-D) as a screening instrument for depression among community-residing older adults.* Psychology Aging, 1997. **12**(2): p. 277.
6. Zoccolillo, M., *Parents' health and social adjustment: part II, social adjustment.* Longitudinal study of child development in Québec, 2000: p. 37-45.
7. Pampalon, R. and G. Raymond, *A deprivation index for health and welfare planning in Québec.* Chronic Diseases in Canada, 2000. **21**(3): p. 104-113.
8. Pampalon, R., et al., *An area-based material and social deprivation index for public health in Québec and Canada.* Canadian Journal of Public Health/Revue Canadienne de Sante'e Publique, 2012: p. S17-S22.

Chapter 5: Discussion

5.1 General Summary

The overarching aim of this dissertation was to document the associations between greenspace exposure and internalizing and externalizing mental health problem symptoms and suicide-related outcomes across the lifespan, while accounting for key confounding variables at the individual, family, and neighborhood levels. Additionally, it was also intended to evaluate the potential moderating roles of socioeconomic status and sex between these associations.

First, the results from our systematic review (**Chapter 3**) demonstrated that among the 23 included articles, exposure to greenspace was associated with lower suicide-related outcomes (i.e., suicide mortality, self-harm, suicidal ideation), with 64% of associations showing a positive association, particularly among females. However, 34% of the findings did not report beneficial associations between greenspace exposure and suicide-related outcomes. Importantly, all of the included studies evaluated the association between greenspace exposure and suicide-related outcomes in urban environments, with only one study carrying out additional analyses in a rural environment. The included articles were mostly observational research designs (n = 21/23 studies) with a focus of suicide mortality as the main outcome (n = 14/23 studies), followed by suicidal ideation (n = 6/23 studies) and self-harm (n = 5/23 studies). Additionally, 87% of the articles used an objective greenspace measure which was typically evaluated as the proportion of greenspace within a given area and the level of surrounding greenness assessed via the NDVI using satellite remote sensing data. Moreover, the included articles generally adequately adjusted for confounding factors at the household (e.g., income, employment status) and area levels (e.g., deprivation indices), although individual level factors were seldomly considered.

Second, the findings from our longitudinal study using data from the Québec Longitudinal Study of Child Development (**Chapter 4**) highlighted that among 742 urban-dwelling youth, increasing levels of residential greenspace (around a 250 m buffer zone) in childhood at age 10 years was associated with fewer symptoms of inattention problems in adolescents aged 15-17 years. Adjusting for key confounding variables at the individual (sex, childhood mental health), family (family socioeconomic status, maternal age at birth, parental mental health, family composition) and neighborhood (material and social deprivation) levels only slightly attenuated this association, which remained significant. Sensitivity analyses revealed a similar pattern of results in buffer zones of 500 m and 1000 m. Moreover, this study evaluated these associations across a wide range of mental health problem symptoms including, hyperactivity/impulsivity, depressive and anxiety symptoms, conduct problems, and suicidal ideation. However, childhood residential greenspace exposure was not observed to be significantly associated with these outcomes in adolescence. Additionally, effect moderation with family socioeconomic status and sex were not significant, suggesting that the beneficial associations of greenspace exposure were observable for female and male Québec youth across all socioeconomic backgrounds.

5.2 Greenspace Exposure Metrics

It has been demonstrated that different greenspace exposure metrics yield different results depending on the mental health outcome being evaluated (Jarvis et al., 2020; Larkin & Hystad, 2019). This is important to consider as the overall literature varies greatly on the greenspace exposure metric used in studies, which may have an influence on the observed associations. With regards to this dissertation, the greenspace metrics used in **Chapters 3 and 4** were objective measures. Specifically, the results from our systematic review illustrated that 91%

of the included studies evaluated objective measures such as the level of greenness surrounding a given area, the quantity of greenspace, percentage of green canopy, and structural features of greenspace (i.e., landscape metrics). In our longitudinal study, we used the NDVI metric to serve as a proxy for residential surrounding greenness.

Objective measures are most commonly used in the literature (Labib et al., 2020b), especially the use of the NDVI given the ease in linking area units with the metric and interpreting its results, as well as the applicability of this measure across disciplines (Pettorelli, 2013). In terms of the NDVI metric, most of the included studies in **Chapter 3** evaluated associations across several buffer zones, allowing for a comprehensive understanding regarding the observed associations. Additionally, in **Chapter 4**, we evaluated associations across a diverse range of buffer zones (i.e., 250 m, 500 m, 1000 m) to highlight the robustness of the results. Buffer zones have been hypothesized to give insight regarding the potential individuals have to come into contact with greenspace (e.g., <100 m represents vegetation close to the residence and the possibility to offer stress relief and >100 m represents vegetation visible outside of the residential area related to opportunities for social cohesion and physical activity) (Jarvis et al., 2020; Markevych et al., 2017).

Moreover, objective measures offer an over-head perspective of greenspace, and do not capture eye-level interactions with greenspace (Rosenberg, 2017; Wang et al., 2021). For instance, objective measures do not capture specific qualities or perceptions of greenspace (i.e., subjective measures). In **Chapter 3**, only one of the included studies evaluated a subjective measure of greenspace (i.e., perceived decrease in time spent in greenspace assessed via a questionnaire) (Holman et al., 2023). Previous studies have illustrated that in addition to the use of objective greenspace measures, subjective measures such as quality, perceived connection to

greenspace, and perceived access to greenspace have been associated with improved mental health symptoms (Collins et al., 2020; McCormick, 2017; Y. Zhang et al., 2020). Future studies could therefore incorporate subjective measures of greenspace exposure to help get a more comprehensive picture of eye-level experiences that could further inform the potential benefits of greenspace exposure on mental health.

5.3 Confounding Factors

The body of research presented in this dissertation included predominantly observational research designs. Consequently, it is important to highlight the role of confounding factors across the individual, family, and area levels as such factors have the potential to influence the observed associations. In **Chapter 3**, 91% of the included studies were observational research designs and most of these studies adequately adjusted for various confounding factors at the household and area levels, including socioeconomic status, employment status, population density, and deprivation indices, to name a few. However, given that most studies were an ecological design (i.e., data aggregated at the area level), confounding factors at the individual level were scarce, and studies that did adjust for individual level variables included predominantly sex and age. These findings regarding confounding factors echo those from elsewhere which highlighted that the inclusion of individual level confounding factors remains a limitation in the body of literature evaluating greenspace exposure and mental health (Roberts et al., 2019).

In **Chapter 4**, a series of confounding factors were included in the analyses ranging across the individual, family, and neighborhood levels (in line with other research (Mavoa et al., 2019; Reuben et al., 2019)), with the inclusion of childhood mental health problem symptoms and parental mental health, which extends prior knowledge. Although not published in the final manuscript, a directed acyclic graph (DAG) was completed to offer reviewers an objective

justification for the inclusion of the confounding factors in the study (**Appendix A**). While the DAG corroborated the included confounding factors at the individual, family, and neighborhood levels, it was not possible to adjust for ethnicity as this variable was not available in the Québec Longitudinal Study of Child Development (QLSCD) at the childhood timepoint evaluated. Moreover, there has been recent interest in the role of genetic variables as factors to consider when evaluating the associations between greenspace exposure and mental health (Roberts et al., 2019). It has been hypothesized that genetic predispositions influence characteristics and behaviors, which in turn affect involvement with natural environments (Belsky et al., 2019; Engemann et al., 2020). In particular, it has been documented that there are two main advantages of adjusting for genetic variables when evaluating selection effects including that (1) genotypes cannot be caused by the natural environment (e.g., greenspace, neighborhood), ruling out reverse causation and (2) genetics may provide novel information over and above what can be measured by self-report health measures (Belsky et al., 2019). Indeed, the selection of variables potentially influencing the associations between greenspace exposure and mental health are important for researchers to consider, especially as factors across individual, family/household, and area levels are at play simultaneously.

5.4 Pathways Linking Greenspace to Mental Health Across Chapters 3 and 4

Our findings that increasing levels of childhood levels of residential greenspace exposure was associated with lower symptoms of inattention problems in adolescence (**Chapter 4**) is in line with a growing body of evidence from systematic reviews (Fyfe-Johnson et al., 2021; Sakhvidi et al., 2022; Tran et al., 2022) and several longitudinal studies (Donovan et al., 2019; Markevych et al., 2018; Reuben et al., 2019; Thygesen et al., 2020). Although most of the literature has examined the associations of greenspace exposure on cognitive development in

youth populations, there is some evidence from population-based cohort studies that has highlighted similar associations in adults (De Keijzer et al., 2018; Jimenez et al., 2022; Zijlema et al., 2017). Collectively, these findings from across the lifespan illustrate the restorative capacities of greenspace exposure, in line with the Attention Restoration Theory. This theory suggests that interactions with greenspace can enhance directed attention abilities (Kaplan & Kaplan, 1989; Kaplan, 1995), which is particularly important given rapid urbanization. Urban environments require constant attention to filter through various stimuli which is taxing on attention resources and contributes to overall feelings of fatigue (Berman et al., 2008). Exposure to greenspace in these environments may aid in reducing the strain of this deliberate and directed attention which has been noted to be a by-product of fast-paced urban environments (Berman et al., 2008).

Moreover, although the following analyses were not included in the publication of **Chapter 4**, we examined whether physical activity mediated the associations between greenspace exposure and mental health outcomes. The results were non-significant, suggesting that physical activity did not mediate the association between inattention problems and residential greenspace exposure in our sample. Our decision to have not included these analyses was also due to the potential for measurement error of the physical activity items, wherein the person most knowledgeable to the child reported on their structured (e.g., sports with a coach) and unstructured (e.g., unorganized sports without an instructor) physical activity over the last 12 months (Guèvremont et al., 2008; Piché et al., 2019).

Although the mechanisms driving the associations between greenspace exposure and suicide-related outcomes remain largely unknown and was not an aim of **Chapter 3**, there are several hypotheses that can be considered. For instance, there has been evidence to suggest that

in adult populations, perhaps the building capacity of greenspace to encourage physical activity plays a role (Shen et al., 2022). Findings have demonstrated that this is likely given that greenspace has the potential to promote physical activity and consequently good mental health, thereby potentially lowering suicide mortality (Akpinar, 2016; Dadvand et al., 2016; Nieuwenhuijsen et al., 2017). Additionally, a systematic review and meta-analysis revealed that across 22 included studies, loneliness was a significant predictor of suicide-related outcomes. (McClelland et al., 2020). In another systematic review (n = 22 studies), it was found that greenspace exposure was inversely associated with loneliness in 66.6% of the observed associations (Astell-Burt et al., 2022). It is plausible that perhaps loneliness plays a role in the associations between greenspace exposure and suicide-related outcomes, although future work would be required to test this pathway further.

Collectively, it is clear that the mechanisms driving associations between greenspace exposure and mental health and suicide are complex, requiring further evaluation. To help bring more cohesion to the field, Cardinali et al. (2023) developed a checklist of assessment decisions that investigators could undertake based on the theoretical pathways between greenspace exposure and mental health proposed by Markevych et al. (2017). The developed checklist assists researchers in navigating from the initial research inquiry to defining greenspace accurately, which is based on the primary theoretical pathway (Cardinali et al., 2023). Once this is established, the following steps include determining suitable greenspace metrics while incorporating essential contextual variables (Cardinali et al., 2023) (**Appendix B**). Although the checklist was published after the publication of **Chapters 3 and 4**, it provides researchers with a systematic step-by-step procedure to help select appropriate research questions that stem from

best practice in the field of environmental health science, especially in terms of greenspace exposure.

5.5 Environmental Injustice

Environmental injustices concerning greenspace exposure manifest through many disparities, which have been highlighted in the findings obtained across **Chapters 3 and 4**.

In **Chapter 4**, although socioeconomic status did not moderate the observed associations, we found that socioeconomically disadvantaged youth resided in neighborhoods with lower levels of greenspace. The disparity in greenspace accessibility for socioeconomically deprived individuals has implications for mental health. Studies have demonstrated that individuals living in socioeconomically disadvantaged neighborhoods have limited access to greenspace compared to their socioeconomically advantaged counterparts (Browning & Lee, 2017; Mitchell & Popham, 2008; Wolch et al., 2014). Limited access to greenspace in socioeconomically deprived areas exacerbates existing health inequities, as these communities often face higher levels of environmental stressors, such as air and noise pollution, limited green infrastructure, and higher crime rates (Hajat et al., 2021; Hipp & Wickes, 2017; Mathiarasan & Hüls, 2021). The absence of greenspace deprives residents of opportunities for physical activity, social interaction, and restoration, which are important for maintaining positive mental health. Furthermore, greenspaces in socioeconomically advantaged neighborhoods are often better maintained, with more amenities and recreational facilities, making them more attractive and conducive to leisure activities (Cao et al., 2020; Jim & Shan, 2013; Vaughan et al., 2013). In contrast, greenspaces in socioeconomically deprived areas may be neglected, poorly maintained, or perceived as unsafe, discouraging residents from using them (Hoffimann et al., 2017; Jones et al., 2009). The lack of greenspace access contributes to the perpetuation of socioeconomic disparities in mental health

outcomes, as socioeconomically deprived individuals are more likely to experience mental health problem symptoms, such as anxiety and depression associated with environmental deprivation (Lorant et al., 2003; Marmot, 2013).

Furthermore, in **Chapter 3**, associations between greenspace exposure and suicide-related outcomes were stronger for females, compared to males. The disparity in greenspace exposure benefits favoring females over males may stem from various mechanisms, including differences in access and safety concerns (Bolte et al., 2019; Sillman et al., 2022). Females tend to use greenspace more frequently for recreational and leisure activities, such as walking, jogging, or socializing, compared to males (Currie et al., 2016; Stafford et al., 2005). However, access to greenspace may be hindered by factors such as proximity, transportation limitations, or perceptions of safety, particularly in urban areas where greenspace may be less accessible or perceived as less secure (Kavanagh et al., 2006; Richardson & Mitchell, 2010). Safety concerns can significantly impact greenspace use, with females often expressing higher levels of apprehension regarding safety in outdoor environments, especially during certain times of the day or in poorly lit areas (Ceccato & Loukaitou-Sideris, 2022; Derose et al., 2018; Sonti et al., 2020). Fear of harassment or violence may deter females from accessing greenspaces, limiting opportunities for physical activity, attention restoration, and stress reduction associated with greenspace exposure (Basu & Nagendra, 2021; Haase et al., 2017; Sreetheran & Van Den Bosch, 2014). Moreover, greenspaces may not necessarily be designed or managed with the specific needs and preferences of females in mind. Lack of amenities such as well-lit paths, public restrooms, or community programming can further hinder a female's engagement with greenspaces.

While it was not possible to control for ethnicity in **Chapter 4** as this variable was not available at the childhood timepoint used in QLSCD database, the results from **Chapter 3** further illustrated that ethnicity was not a variable extensively evaluated in the included studies of the systematic review. The disparity in greenspace access for minority ethnicities contributes to environmental injustices and exacerbates existing health disparities (Fernandez et al., 2021). It has been documented that communities of color often face disproportionate barriers to accessing high-quality greenspaces compared to white populations (Dai, 2011; Kephart, 2022; Roe et al., 2016). These disparities may be rooted in historical and systemic factors such as residential segregation, discriminatory urban planning policies, and unequal distribution of resources (Apparicio et al., 2012; de Souza & Torres, 2021; Riley, 2018). In many urban areas in middle to high income regions, greenspaces are predominantly located in affluent, majority white neighborhoods, while minority neighborhoods are often characterized by limited greenspace availability and poorer greenspace quality (Mizutani, 2018; Pastor et al., 2001). This lack of access could potentially deprive minority communities of the physical and mental health benefits associated with greenspace exposure, perpetuating health inequities. Furthermore, greenspaces in minority neighborhoods may suffer from neglect, lack of maintenance, and safety concerns, making them less attractive and under used by residents (Klompmaker et al., 2023; Rigolon, 2016). Discriminatory practices, such as over-policing or racial profiling in public areas, can also contribute to feelings of exclusion and discomfort among minority individuals, further limiting their engagement with greenspaces (Boehme et al., 2022; Fernandez et al., 2021; Plümecke et al., 2023). A recent narrative review (n =10 studies) identified that a lack of diversity-friendly factors, such as multiple languages on signs and available prayer spaces in greenspaces may further contribute to individuals from minority ethnic groups having hesitation to use

greenspaces (Robinson et al., 2022). Moreover, most research on greenspace exposure and mental health has been conducted in high-income countries, predominantly in urban settings (as was observed in **Chapter 3** and documented elsewhere (Marvier et al., 2023). This limits our understanding of how greenspace exposure affects mental health in low-income countries and marginalized populations. This gap in knowledge hinders efforts to address environmental injustices and promote health equity on a global scale.

Moreover, it has been documented that the suicide mortality rate is higher for individuals residing in rural regions (Casant & Helbich, 2022; Hirsch & Cukrowicz, 2014), which has been recently corroborated in Québec (Levesque & Perron, 2024). This is particularly puzzling considering that rural regions are marked by more greenspace in comparison to urban environments (Browning et al., 2022). In **Chapter 3**, only one of the included studies evaluated the associations between greenspace exposure and suicide mortality in rural regions, and found that rural greenspace exposure was protective for males but not females (Jiang et al., 2021). Future work is needed to clarify the role of rural greenspace and its association with suicide-related outcomes, given differences in urban-rural environments which are documented determinants of suicide (e.g., population density, exposure to air pollutants) (Casant & Helbich, 2022; Zhou et al., 2022).

Overall, addressing these disparities requires comprehensive strategies focusing on equitable distribution of greenspace, urban planning policies, and community engagement initiatives to ensure equal access and benefits for all individuals, regardless of socioeconomic status, sex/gender, ethnicity, or urban-rural gradients.

5.6 Strengths and Limitations

There are notable strengths of the published articles included in this dissertation, including that this body of doctoral work was the first to synthesize the available evidence documenting the associations between greenspace exposure and suicide-related outcomes (**Chapter 3**). Additionally, the use of data from a well-characterized Canadian cohort which allowed for (a) the evaluation of greenspace exposure in childhood and a wide range of mental health outcomes in adolescence, (b) the inclusion of several confounding factors at the individual, family, and neighborhood levels, and (c) the evaluation of these associations across several buffer zones (250 m, 500 m, 1000 m) (**Chapter 4**). However, several limitations need to be noted.

First, the greenspace metrics used across **Chapters 3 and 4** were predominantly objective, with only one study in **Chapter 3** that adopted a subjective greenspace metric. While objective measures provide an overhead perspective of greenspace, which can be beneficial when studying whole populations, these measures do not capture eye-level perspectives of greenspace such as quality and access, which provides context regarding individual experiences in greenspace (Wang et al., 2021). Consequently, further research using subjective greenspace exposure metrics are warranted.

Second, the doctoral research presented in **Chapters 3 and 4** was predominantly observational in nature. Therefore, the presence of potential unmeasured confounding factors cannot be ruled out. Although confounding factors were carefully selected across the individual, family, and neighborhood levels in **Chapter 4**, the results from **Chapter 3** highlighted that there are inconsistencies in confounding factor selection, especially in terms of greenspace exposure and suicide-related outcomes. Future work on the associations between greenspace exposure and

mental health outcomes should consider whether narrative descriptions of the confounder selection process based on extensive literature review, or the use of a DAG would be most appropriate in their research designs.

Third, while the doctoral research presented in **Chapters 3 and 4** did not explicitly aim to assess the mechanisms driving the associations between greenspace exposure and mental health, it strongly advocates for future studies to delve deeper into these pathways. For instance, the results obtained in **Chapter 4** are in support of the restorative capacities of greenspace exposure, particularly in parallel with the Attention Restoration Theory. Given the increasing number of studies in the greenspace and health fields (J. Zhang et al., 2020), more standardized procedures are needed to help researchers address research questions in a systematic way (Cardinali et al., 2023).

Fourth, the results obtained from **Chapter 3** highlighted that there is a dire need for experimental studies that can evaluate the role of greenspace exposure in mitigating suicidal risk, corroborating with a recent systematic review which highlighted that there were no sufficiently powered or pre-registered experimental studies which evaluated the causal role of greenspace exposure and well-being (Folk & Dunn, 2023). In our systematic review, the need for experimental studies was especially true for youth populations, as none of the two included experimental studies in the review evaluated the causal influence of greenspace exposure on youth mental health. While a copious number of observational studies have highlighted the associations between greenspace exposure and mental health (including suicide-related outcomes), experimental designs, particularly randomized controlled trials, enable investigators to manipulate greenspace exposure directly. Additionally, these research designs can minimize the influence of confounding factors given the ability to control setting variables (thus enhancing

the reliability of results) as well as holding the potential to explore theoretical pathways linking greenspace to mental health via the manipulation of exposure levels and specific outcomes.

Fifth, further clarifications regarding the associations between greenspace exposure and sex/gender are needed. In **Chapter 3**, it was found that in studies that stratified their analyses by sex, females showed lowered suicidal risk with increased greenspace exposure. Alternatively, in **Chapter 4**, the role of greenspace exposure in lowering symptoms of inattention was significant for both female and male youth. Moreover, in **Chapters 3 and 4**, sex was treated as a binary construct, in line with a systematic review that identified 62 articles which had also dichotomized findings based on sex (Sillman et al., 2022). However, it would be imperative for future work to explore the role of gender in influencing the associations between greenspace exposure and mental health, especially as it has been proposed that perhaps different mechanisms are involved when considering sex versus gender in these associations (Bolte et al., 2019; Sillman et al., 2022).

5.7 Implications

Overall, the results obtained from this doctoral research supports growing evidence that greenspace exposure can be a pillar of lifestyle health (Sundermann et al., 2023). However, there is still much ground to cover within this field as there is insufficient findings regarding the role of subjective greenspace metrics, including the quality and type of greenspace most beneficial, as well as optimal duration times in green environments for improving mental health, corroborated by a recent systematic review (Folk & Dunn, 2023). Nonetheless, the findings from **Chapters 3 and 4** contribute to numerous initiatives across various domains (e.g., primary care, psychology, education, urban planning) that encourage the use of greenspace as a complimentary strategy to boost mental health and well-being.

To illustrate, greenspace prescriptions consist of a new model of care which involves the referral from a health professional (e.g., general practitioner, nurse) recommending a patient to spend a fixed amount of time each week in a natural setting, such as a forest or park (James et al., 2019). These initiatives have been implemented in Canada (Parks Canada, 2014), Québec (Prescri-Nature, 2024) as well as in Europe (National Health Service England, 2024). A recent meta-analysis found that greenspace prescriptions (i.e., a prescription given by a health care professional to promote time spent in greenspaces) had a moderate to large effect on depression and anxiety scores, in comparison to baseline scores prior to commencing the prescriptions (Nguyen et al., 2023).

In parallel, leveraging the use of greenspace in traditional psychotherapy treatment could be a novel avenue for psychologists. For instance, a randomized controlled trial conducted by our own research team has highlighted that for outpatient adults with a refractory depression diagnosis, a walk in a green park (in comparison to an urban walk) was associated with lower levels of negative affect in comparison to baseline scores prior to the walk (Watkins-Martin et al., 2021). These findings demonstrate that perhaps psychologists could integrate green walks in traditional psychotherapy sessions, although further research would be warranted.

Additionally, the enthusiasm regarding the benefits of greenspace exposure and mental health is also shared by the world of education, where a growing (but still limited) number of teachers practice outdoor education with aims similar to those of green-based interventions implemented in primary care contexts. For instance, the practice of outdoor education (i.e., teaching curriculum off campus) has been increasing in Canada, with more teachers bringing students outdoors to learn (Ayotte-Beaudet et al., 2023). In fact, there is an on-going randomized controlled trial taking place in the province of Québec led by Dr. Geoffroy which aims to test the

effectiveness of a green-based school intervention designed to decrease mental health symptoms in school-aged children (Loose et al., 2023).

Lastly, a recent review highlighted that greenspace is more beneficial for health among individuals residing in urban areas in comparison to those residing in rural areas (Browning et al., 2022). This may be due to urban dwellers having "more to gain" from greenspace given the various mechanisms in which greenspace promotes health (e.g., reduction of harmful exposures, restoration of attentional abilities, promotion of social and physical activities, and development of the human microbiome) (Browning et al., 2022; Markevych et al., 2017). Additionally, a recent commentary from UNICEF also highlighted that urban green environments are crucial for child development (Chawla, 2021). Consequently, urban planning initiatives could involve strategically integrating greenspaces within urban environments, ensuring equitable access, and considering their impact across the biopsychosocial spheres for individuals across the lifespan.

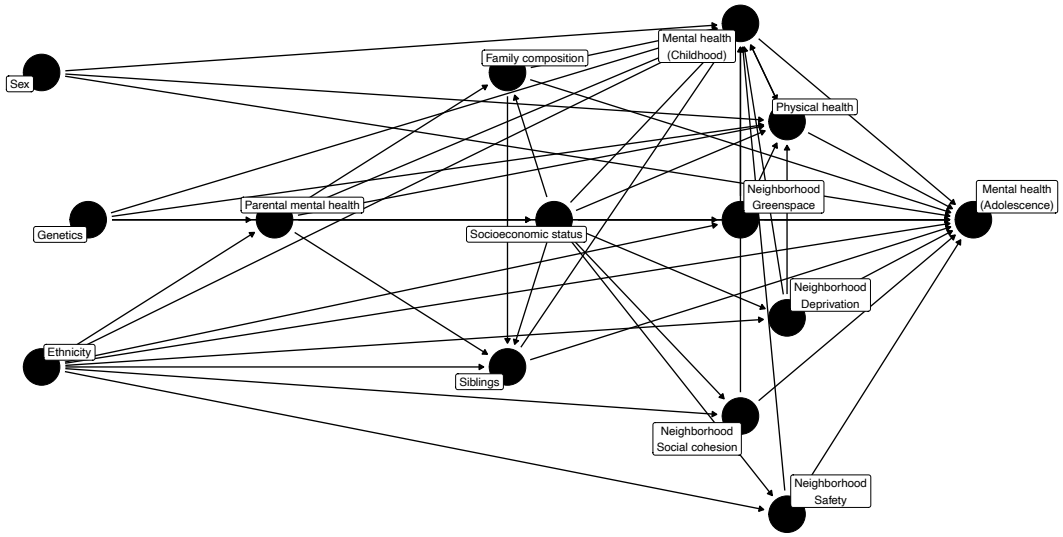
Collectively, these initiatives across the domains of primary care, psychology, education, and urban planning, alongside the results obtained from this doctoral research, provide evidence that greenspace exposure has immense potential to help individuals from across the lifespan cope with symptoms of mental health.

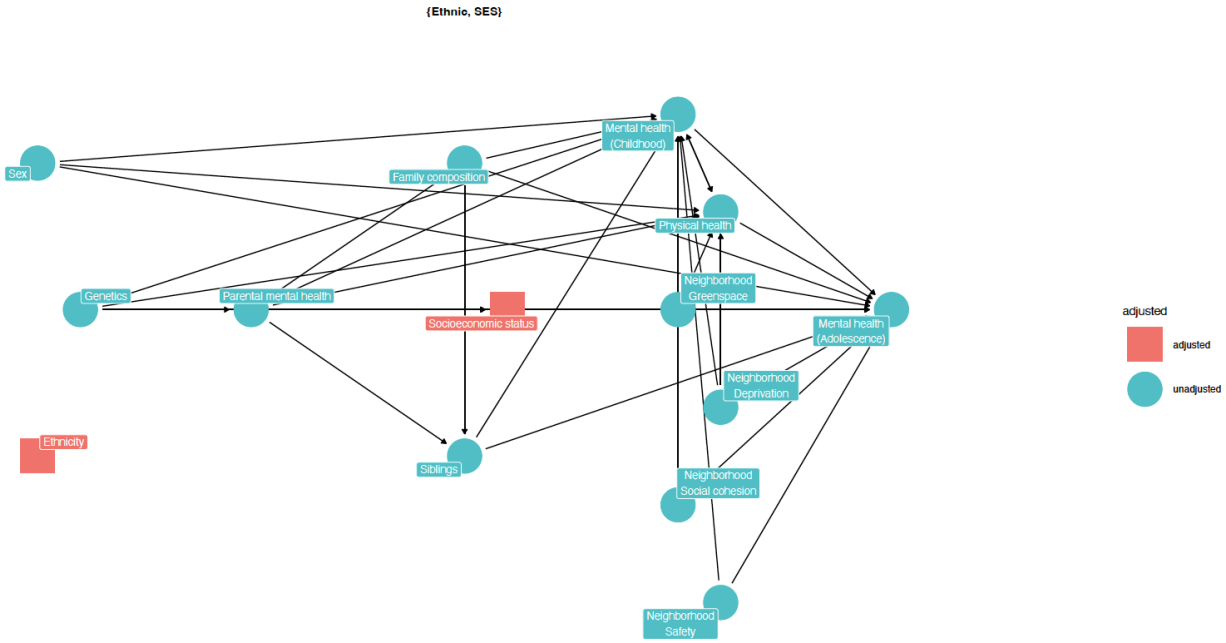
Conclusion

There has been increasing interest in the putative benefits of greenspace exposure and the full spectrum of mental health outcomes. The findings obtained in this dissertation underscore important protective associations between greenspace exposure and mental health symptoms, namely for suicide-related outcomes across the lifespan as well as for attention problems in adolescents. The clarification of these associations highlights the restorative capacities of greenspace exposure, marking green environments as a vital environmental resource that could be incorporated in mental health prevention initiatives, particularly in urban environments. Nonetheless, the complexity of these associations calls for further exploration into the underlying mechanisms and moderators, necessitating robust experimental studies that could help establish causal inferences in both youth and adult samples. Additionally, there are several disparities that exist which bring forth environmental injustices impacting low-income regions and minority populations, warranting further investigation. These efforts have the potential to shape new approaches, such as walking interventions or school-based programs in green environments, providing opportunity to help whole populations cope with symptoms of mental health problems, alongside traditional treatment options. It is crucial for further exploration to enhance our understanding of the potential therapeutic value of greenspace exposure to drive progress in mental health care. Indeed, greenspace exposure holds promising potential to serve as an additional pillar of lifestyle health.

Appendix A

Unpublished directed acyclic graph (DAG) used to corroborate confounding factors used in Chapter 4.





Appendix B

Preferred Reporting Items in Greenspace Health Research developed by Cardinali et al. (2023)

#	Section/Topic	Checklist Item	Reported	Page Nr.
	OBJECTIVE			
1	Health Outcome(s)	Specify the health outcome(s) being researched	☐	
2	Pathway(s)	Position the research within a theoretical pathway (Mitigation, Restoration, Instoration).	☐	
3	Green Space Focus	Provide a clear definition of green space features being researched, distinguishing in particular between surrounding vegetation, contact with nature, and accessible green spaces.	☐	
	SCOPE			
4	Type of Distance	Specify the type of distance used with rationale (Euclidean Distance (ED), Network Distance (ND), Buffered Service Area (BSA), Administrative Units (AU)).	☐	
5	Walkability Network	If accessibility to green spaces is part of the study design, indicate if the walkability network used to generate isochrones or buffered service areas has been checked for bias and how.	☐	
6	Distance	Give a rationale for the chosen distance and indicate if different distances were tested (Sensitivity Analysis).	☐	
	SPATIAL ASSESSMENT			
7	Proxy for Exposure Variable	Define the spatial indicators used in research and indicate if different indicators were tested (Sensitivity Analysis).	☐	
8	Data Source	Indicate which database was used and if there has been an adjustment for potential bias (expert assessment).	☐	
9	Public Ownership Bias	Indicate if the dataset was controlled for the usability of green spaces from public-owned plots and how.	☐	
10	Residential Ownership Bias	Indicate how semi-public residential green spaces have been handled.	☐	
11	Classification Bias	Indicate how green spaces have been classified.	☐	
12	Usability Bias	Indicate if the usability of green spaces was checked and report inclusion/exclusion criteria.	☐	
13	Connectivity Bias	(Optional) Indicate if the database has been corrected for green space network connectivity and how.	☐	
	VEGETATIVE ASSESSMENT			
14	Proxy for Exposure Variable	Specify the indicator(s) used to assess surrounding vegetation or nature and indicate if the sensitivity was tested.	☐	
15	Data Source	Provide the data source of the satellite images and their resolution.	☐	
16	Handling of Blue Spaces	Indicate how blue spaces have been handled.	☐	

17	Handling of Seasons	Explain how variance in vegetation indices due to seasonality or changes in the built environment was handled.	☐
	CONTEXT ASSESSMENT		
18	Personal Context	Give a rationale for the chosen personal context variables that have been tested or controlled for.	☐
19	Local Context	Give a rationale for the chosen local context variables that have been tested or controlled for.	☐
20	Urbanicity Context	Give a rationale for the chosen urbanicity context variables that have been tested or controlled for.	☐
21	Global Context	Indicate in which climate, and cultural setting the study was conducted. If several settings are part of the research explain how the results were controlled for potential confounding and tested for effect modification.	☐

References

‘Yotti’Kingsley, J., & Townsend, M. (2006). ‘Dig in’to social capital: Community gardens as mechanisms for growing urban social connectedness. *Urban policy and research*, *24*(4), 525-537. https://doi.org/10.1080/08111140601035200

Akpinar, A. (2016). How is quality of urban green spaces associated with physical activity and health? *Urban Forestry Urban Greening*, *16*, 76-83. https://doi.org/10.1016/j.ufug.2016.01.011

Akpınar, A. (2021). How perceived sensory dimensions of urban green spaces are associated with teenagers’ perceived restoration, stress, and mental health? *Landscape and Urban Planning*, *214*, 104185. https://doi.org/10.1016/j.landurbplan.2021.104185

Almanza, E., Jerrett, M., Dunton, G., Seto, E., & Pentz, M. A. (2012). A study of community design, greenness, and physical activity in children using satellite, GPS and accelerometer data. *Health & place*, *18*(1), 46-54. https://doi.org/10.1016/j.healthplace.2011.09.003

American Psychiatric Association. (2022). *Diagnostic and statistical manual of mental disorders: DSM-5* (5th ed.). American Psychiatric Association. http://www.PsychiatryOnline.org

Apparicio, P., Séguin, A.-M., Landry, S., & Gagnon, M. (2012). Spatial distribution of vegetation in Montreal: an uneven distribution or environmental inequity? *Landscape and urban planning*, *107*(3), 214-224. https://doi.org/10.1016/j.landurbplan.2012.06.002

Arsenault-Lapierre, G., Kim, C., & Turecki, G. (2004). Psychiatric diagnoses in 3275 suicides: a meta-analysis. *BMC Psychiatry*, *4*(1), 1-11. https://doi.org/https://doi.org/10.1186/1471-244X-4-37

Astell-Burt, T., Feng, X., & Kolt, G. S. (2013). Green space is associated with walking and moderate-to-vigorous physical activity (MVPA) in middle-to-older-aged adults: findings from 203 883 Australians in the 45 and Up Study. *British Journal of Sports Medicine*. https://doi.org/10.1136/bjsports-2012-092006

Astell-Burt, T., Hartig, T., Putra, I. G. N. E., Walsan, R., Dendup, T., & Feng, X. (2022). Green space and loneliness: A systematic review with theoretical and methodological guidance for future research. *Science of the Total Environment*, *847*, 157521. https://doi.org/10.1016/j.scitotenv.2022.157521

Ayotte-Beaudet, J.-P., Berrigan, F., Deschamps, A., L'Heureux, K., Beaudry, M.-C., & Turcotte, S. (2023). K-11 teachers' school-based outdoor education practices in the province of Québec, Canada: from local initiatives to a grassroots movement. *Journal of Adventure Education and Outdoor Learning*, 1-14. https://doi.org/10.1080/14729679.2022.2164787

Balseviciene, B., Sinkariova, L., Grazuleviciene, R., Andrusaityte, S., Uzdanaviciute, I., Dedele, A., & Nieuwenhuijsen, M. J. (2014). Impact of residential greenness on preschool children's emotional and behavioral problems. *International Journal of Environmental Research Public Health*, *11*(7), 6757-6770. https://doi.org/10.3390/ijerph110706757

Bannari, A., Morin, D., Bonn, F., & Huete, A. (1995). A review of vegetation indices. *Remote sensing reviews*, *13*(1-2), 95-120. https://doi.org/10.1080/02757259509532298

Basu, S., & Nagendra, H. (2021). Perceptions of park visitors on access to urban parks and benefits of green spaces. *Urban Forestry & Urban Greening*, *57*, 126959. https://doi.org/10.1016/j.ufug.2020.126959

Belsky, D. W., Caspi, A., Arseneault, L., Corcoran, D. L., Domingue, B. W., Harris, K. M., Houts, R. M., Mill, J. S., Moffitt, T. E., & Prinz, J. (2019). Genetics and the geography of

health, behaviour and attainment. *Nature human behaviour*, *3*(6), 576-586. https://doi.org/10.1038/s41562-019-0562-1

Berman, M. G., Jonides, J., & Kaplan, S. (2008). The cognitive benefits of interacting with nature. *Psychological science*, *19*(12), 1207-1212. https://doi.org/10.1111/j.1467-9280.2008.02225.x

Boehme, H. M., Cann, D., & Isom, D. A. (2022). Citizens' perceptions of over-and under-policing: a look at race, ethnicity, and community characteristics. *Crime & Delinquency*, *68*(1), 123-154. https://doi.org/10.1177/0011128720974309

Bolte, G., Nanninga, S., & Dandolo, L. (2019). Sex/Gender Differences in the Association between Residential Green Space and Self-Rated Health—A Sex/Gender-Focused Systematic Review. *International Journal of Environmental Research Public Health*, *16*(23), 4818. https://doi.org/10.3390/ijerph16234818

Bornioli, A., Parkhurst, G., & Morgan, P. L. (2018). The psychological wellbeing benefits of place engagement during walking in urban environments: A qualitative photo-elicitation study. *Health & place*, *53*, 228-236. https://doi.org/10.1016/j.healthplace.2018.08.018

Boudier, A., Markevych, I., Jacquemin, B., Abramson, M. J., Accordini, S., Forsberg, B., Fuertes, E., Garcia-Aymerich, J., Heinrich, J., & Johannessen, A. (2022). Long-term air pollution exposure, greenspace and health-related quality of life in the ECRHS study. *Science of the Total Environment*, *849*, 157693. https://doi.org/10.1016/j.scitotenv.2022.157693

Braithwaite, I., Zhang, S., Kirkbride, J. B., Osborn, D. P., & Hayes, J. F. (2019). Air pollution (particulate matter) exposure and associations with depression, anxiety, bipolar,

psychosis and suicide risk: a systematic review and meta-analysis. *Environ Health Perspect*, *127*(12), 126002. https://doi.org/10.1289/EHP4595.

Brame, J. E., Liddicoat, C., Abbott, C. A., & Breed, M. F. (2021). The potential of outdoor environments to supply beneficial butyrate-producing bacteria to humans. *Science of the Total Environment*, *777*, 146063. https://doi.org/10.1016/j.scitotenv.2021.146063

Bratman, G. N., Hamilton, J. P., & Daily, G. C. (2012). The impacts of nature experience on human cognitive function and mental health. *Annals of the New York academy of sciences*, *1249*(1), 118-136. https://doi.org/10.1111/j.1749-6632.2011.06400.x

Brown, S. C., Perrino, T., Lombard, J., Wang, K., Toro, M., Rundek, T., Gutierrez, C. M., Dong, C., Plater-Zyberk, E., & Nardi, M. I. (2018). Health disparities in the relationship of neighborhood greenness to mental health outcomes in 249,405 US Medicare beneficiaries. *International Journal of Environmental Research Public Health*, *15*(3), 430. https://doi.org/10.3390/ijerph15030430

Browning, M., & Lee, K. (2017). Within what distance does "greenness" best predict physical health? A systematic review of articles with GIS buffer analyses across the lifespan. *Int J Environ Res Public Health*, *14*(7), 675. https://doi.org/10.3390/ijerph14070675

Browning, M. H., Rigolon, A., & McAnirlin, O. (2022). Where greenspace matters most: A systematic review of urbanicity, greenspace, and physical health. *Landscape and Urban Planning*, *217*, 104233. https://doi.org/10.1016/j.landurbplan.2021.104233

Buijs, A. E., Elands, B. H., & Langers, F. (2009). No wilderness for immigrants: Cultural differences in images of nature and landscape preferences. *Landscape and urban Planning*, *91*(3), 113-123. https://doi.org/10.1016/j.landurbplan.2008.12.003

Byrne, J., & Yang, J. (2009). Can urban greenspace combat climate change? Towards a subtropical cities research agenda. *Australian Planner*, *46*(4), 36-43. https://doi.org/10.1080/07293682.2009.10753420

Cao, W., Wu, D., Huang, L., & Liu, L. (2020). Spatial and temporal variations and significance identification of ecosystem services in the Sanjiangyuan National Park, China. *Scientific Reports*, *10*(1), 6151. https://doi.org/10.1038/s41598-020-63137-x

Cardinali, M., Beenackers, M. A., van Timmeren, A., & Pottgiesser, U. (2023). Preferred reporting items in green space health research. Guiding principles for an interdisciplinary field. *Environmental Research*, 115893. https://doi.org/10.1016/j.envres.2023.115893

Casant, J., & Helbich, M. (2022). Inequalities of suicide mortality across urban and rural areas: A literature review. *Int J Environ Res Public Health*, *19*(5), 2669. https://doi.org/10.3390/ijerph19052669

Ceccato, V., & Loukaitou-Sideris, A. (2022). Fear of sexual harassment and its impact on safety perceptions in transit environments: a global perspective. *Violence against women*, *28*(1), 26-48. https://doi.org/10.1177/1077801221992874

Chawla, L. (2021). The Necessity of Urban Green Space for Children's Optimal Development: A Discussion Paper by Suchitra Sugar. *Children, Youth and Environments*, *31*(3), 180-182. https://doi.org/10.1353/cye.2021.a848908

Chiabai, A., Quiroga, S., Martinez-Juarez, P., Suárez, C., de Jalón, S. G., & Taylor, T. (2020). Exposure to green areas: Modelling health benefits in a context of study heterogeneity. *Ecological Economics*, *167*, 106401. https://doi.org/10.1016/j.ecolecon.2019.106401

Clarke, T. B., Davis, K. M., Lysenko, E. S., Zhou, A. Y., Yu, Y., & Weiser, J. N. (2010). Recognition of peptidoglycan from the microbiota by Nod1 enhances systemic innate immunity. *Nature medicine*, *16*(2), 228-231. https://doi.org/10.1038/nm.2087

Clayton, S. (2021). Climate change and mental health. *Current Environmental Health Reports*, *8*, 1-6. https://doi.org/10.1007/s40572-020-00303-3

Clifford, M. A. (2021). What is Forest Bathing? In *Your guide to forest bathing (expanded edition): Experience the healing power of nature* (pp. 1-14). Red Wheel.

Cohen-Cline, H., Turkheimer, E., & Duncan, G. E. (2015). Access to green space, physical activity and mental health: a twin study. *J Epidemiol Community Health*, *69*(6), 523-529. https://doi.org/10.1136/jech-2014-204667

Collins, P. Y., Patel, V., Joestl, S. S., March, D., Insel, T. R., Daar, A. S., Bordin, I. A., Costello, E. J., Durkin, M., & Fairburn, C. (2011). Grand challenges in global mental health. *Nature*, *475*(7354), 27-30. https://doi.org/10.1038/475027a

Collins, R. M., Spake, R., Brown, K. A., Ogutu, B. O., Smith, D., & Eigenbrod, F. (2020). A systematic map of research exploring the effect of greenspace on mental health. *Landscape Urban Planning*, *201*, 103823. https://doi.org/10.1016/j.landurbplan.2020.103823

Cuijpers, P., Miguel, C., Ciharova, M., Kumar, M., Brander, L., Kumar, P., & Karyotaki, E. (2023). Impact of climate events, pollution, and green spaces on mental health: An umbrella review of meta-analyses. *Psychological Medicine*, 1-16. https://doi.org/10.1017/S0033291722003890

Currie, M. J., Lackova, P., & Dinnie, E. (2016). Greenspace matters: exploring links between greenspace, gender and well-being with conservation volunteers. *Landscape research*, *41*(6), 641-651. https://doi.org/10.1080/01426397.2016.1208813

Dadvand, P., Bartoll, X., Basagaña, X., Dalmau-Bueno, A., Martinez, D., Ambros, A., Cirach, M., Triguero-Mas, M., Gascon, M., & Borrell, C. (2016). Green spaces and General Health: Roles of mental health status, social support, and physical activity. *Environ Int*, *91*, 161-167. https://doi.org/10.1016/j.envint.2016.02.029

Dadvand, P., de Nazelle, A., Triguero-Mas, M., Schembari, A., Cirach, M., Amoly, E., Figueras, F., Basagaña, X., Ostro, B., & Nieuwenhuijsen, M. (2012). Surrounding greenness and exposure to air pollution during pregnancy: an analysis of personal monitoring data. *Environ Health Perspect*, *120*(9), 1286-1290. https://doi.org/10.1289/ehp.1104609

Dadvand, P., Rivas, I., Basagaña, X., Alvarez-Pedrerol, M., Su, J., Pascual, M. D. C., Amato, F., Jerret, M., Querol, X., & Sunyer, J. (2015). The association between greenness and traffic-related air pollution at schools. *Science of the Total Environment*, *523*, 59-63. https://doi.org/10.1016/j.scitotenv.2015.03.103

Dai, D. (2011). Racial/ethnic and socioeconomic disparities in urban green space accessibility: Where to intervene? *Landscape and Urban Planning*, *102*(4), 234-244. https://doi.org/10.1016/j.landurbplan.2011.05.002

Davis, Z., Guhn, M., Jarvis, I., Jerrett, M., Nesbitt, L., Oberlander, T., Sbihi, H., Su, J., & van den Bosch, M. (2021). The association between natural environments and childhood mental health and development: A systematic review and assessment of different exposure measurements. *International Journal of Hygiene Environmental Health*, *235*, 113767. https://doi.org/10.1016/j.ijheh.2021.113767

de Keijzer, C., Bauwelinck, M., & Dadvand, P. (2020). Long-term exposure to residential greenspace and healthy ageing: a systematic review. *Current Environmental Health Reports*, *7*(1), 65-88. https://doi.org/10.1007/s40572-020-00264-7

De Keijzer, C., Tonne, C., Basagaña, X., Valentín, A., Singh-Manoux, A., Alonso, J., Antó, J. M., Nieuwenhuijsen, M. J., Sunyer, J., & Dadvand, P. (2018). Residential surrounding greenness and cognitive decline: a 10-year follow-up of the Whitehall II cohort. *Environ Health Perspect*, *126*(7), 077003. https://doi.org/10.1289/EHP2875

de Souza, D. T., & Torres, P. H. C. (2021). Greening and just cities: elements for fostering a south–North dialogue based on a systematic literature review. *Frontiers in Sustainable Cities*, *3*, 669944. https://doi.org/10.3389/frsc.2021.669944

De Vries, S., Buijs, A. E., & Snep, R. P. (2020). Environmental Justice in The Netherlands: Presence and Quality of Greenspace Differ by Socioeconomic Status of Neighbourhoods. *Sustainability*, *12*(15), 5889. https://doi.org/10.3390/su12155889

De Vries, S., Claßen, T., Eigenheer-Hug, S.-M., Korpela, K., Maas, J., Mitchell, R., & Schantz, P. (2011). Contributions of natural environments to physical activity: Theory and evidence base. *Forests, trees and human health*, 205-243. https://doi.org/10.1007/978-90-481-9806-1_8

De Vries, S., Ten Have, M., van Dorsselaer, S., van Wezep, M., Hermans, T., & de Graaf, R. (2016). Local availability of green and blue space and prevalence of common mental disorders in the Netherlands. *BJPsych Open*, *2*(6), 366-372. https://doi.org/10.1192/bjpo.bp.115.002469

Derose, K. P., Han, B., Williamson, S., & Cohen, D. A. (2018). Gender disparities in park use and physical activity among residents of high-poverty neighborhoods in Los Angeles. *Women's Health Issues*, *28*(1), 6-13. https://doi.org/10.1016/j.whi.2017.11.003

Diemer, J., Alpers, G. W., Peperkorn, H. M., Shiban, Y., & Mühlberger, A. (2015). The impact of perception and presence on emotional reactions: a review of research in virtual reality. *Frontiers in Psychology*, *6*, 26. https://doi.org/10.3389/fpsyg.2015.00026

Dimitriu, P. A., Iker, B., Malik, K., Leung, H., Mohn, W. W., & Hillebrand, G. G. (2019). New insights into the intrinsic and extrinsic factors that shape the human skin microbiome. *MBio*, *10*(4), 10-1128. https://doi.org/10.1128/mbio.00839-19

Donovan, G. H., Michael, Y. L., Gatziolis, D., Mannetje, A. t., & Douwes, J. (2019). Association between exposure to the natural environment, rurality, and attention-deficit hyperactivity disorder in children in New Zealand: a linkage study. *The Lancet Planetary Health*, *3*(5), e226-e234. https://doi.org/10.1016/S2542-5196(19)30070-1

Duncan, M. J., Clarke, N. D., Birch, S. L., Tallis, J., Hankey, J., Bryant, E., & Eyre, E. L. (2014). The effect of green exercise on blood pressure, heart rate and mood state in primary school children. *Int J Environ Res Public Health*, *11*(4), 3678-3688. https://doi.org/10.3390/ijerph110403678

Dzhambov, A. M., & Dimitrova, D. D. (2014). Urban green spaces′ effectiveness as a psychological buffer for the negative health impact of noise pollution: A systematic review. *Noise and health*, *16*(70), 157-165. https://doi.org/10.4103/1463-1741.134916

Engemann, K., Pedersen, C. B., Agerbo, E., Arge, L., Børglum, A. D., Erikstrup, C., Hertel, O., Hougaard, D. M., McGrath, J. J., & Mors, O. (2020). Association between childhood

green space, genetic liability, and the incidence of schizophrenia. *Schizophr Bull*, *46*(6), 1629-1637. https://doi.org/10.1093/schbul/sbaa058

Faber Taylor, A., & Kuo, F. E. (2009). Children with attention deficits concentrate better after walk in the park. *Journal of Attention Disorders*, *12*(5), 402-409. https://doi.org/10.1177/1087054708323000

Ferdinand, A. O., Sen, B., Rahurkar, S., Engler, S., & Menachemi, N. (2012). The relationship between built environments and physical activity: a systematic review. *American Journal of Public Health*, *102*(10), e7-e13. https://doi.org/10.2105/AJPH.2012.300740

Fernandez, M., Harris, B., & Rose, J. (2021). Greensplaining environmental justice: A narrative of race, ethnicity, and justice in urban greenspace development. *Journal of Race, Ethnicity and the City*, *2*(2), 210-231. https://doi.org/10.1080/26884674.2021.1921634

Firth, J., Solmi, M., Wootton, R. E., Vancampfort, D., Schuch, F. B., Hoare, E., Gilbody, S., Torous, J., Teasdale, S. B., & Jackson, S. E. (2020). A meta-review of "lifestyle psychiatry": the role of exercise, smoking, diet and sleep in the prevention and treatment of mental disorders. *World Psychiatry*, *19*(3), 360-380. https://doi.org/10.1002/wps.20773

Folk, D., & Dunn, E. (2023). A systematic review of the strength of evidence for the most commonly recommended happiness strategies in mainstream media. *Nature Human Behaviour*, *7*(10), 1697-1707. https://doi.org/10.1038/s41562-023-01651-4

Foster, J. A., Rinaman, L., & Cryan, J. F. (2017). Stress & the gut-brain axis: regulation by the microbiome. *Neurobiology of stress*, *7*, 124-136. https://doi.org/10.1016/j.ynstr.2017.03.001

Fritz, M. S., & Arthur, A. M. (2017). Moderator variables. In *Oxford research encyclopedia of psychology*.

Frost, S., Kannis-Dymand, L., Schaffer, V., Millear, P., Allen, A., Stallman, H., Mason, J., Wood, A., & Atkinson-Nolte, J. (2022). Virtual immersion in nature and psychological well-being: A systematic literature review. *Journal of Environmental Psychology*, *80*, 101765. https://doi.org/10.1016/j.jenvp.2022.101765

Fyfe-Johnson, A. L., Hazlehurst, M. F., Perrins, S. P., Bratman, G. N., Thomas, R., Garrett, K. A., Hafferty, K. R., Cullaz, T. M., Marcuse, E. K., & Tandon, P. S. (2021). Nature and children's health: a systematic review. *Pediatrics*, *148*(4). https://doi.org/10.1542/peds.2020-049155

Geneshka, M., Coventry, P., Cruz, J., & Gilbody, S. (2021). Relationship between Green and Blue Spaces with Mental and Physical Health: A Systematic Review of Longitudinal Observational Studies. *International Journal of Environmental Research Public Health*, *18*(17), 9010. https://doi.org/10.3390/ijerph18179010

Gianfredi, V., Buffoli, M., Rebecchi, A., Croci, R., Oradini-Alacreu, A., Stirparo, G., Marino, A., Odone, A., Capolongo, S., & Signorelli, C. (2021). Association between urban greenspace and health: a systematic review of literature. *Int J Environ Res Public Health*, *18*(10), 5137. https://doi.org/10.3390/ijerph18105137

Gili, M., Castellví, P., Vives, M., de la Torre-Luque, A., Almenara, J., Blasco, M. J., Cebrià, A. I., Gabilondo, A., Pérez-Ara, M. A., & Miranda-Mendizabal, A. (2019). Mental disorders as risk factors for suicidal behavior in young people: A meta-analysis and systematic review of longitudinal studies. *Journal of Affective Disorders*, *245*, 152-162. https://doi.org/https://doi.org/10.1016/j.jad.2018.10.115

Gorini, A., & Riva, G. (2008). Virtual reality in anxiety disorders: the past and the future. *Expert Review of Neurotherapeutics*, *8*(2), 215-233. https://doi.org/10.1586/14737175.8.2.215

Grassini, S. (2022). A Systematic Review and Meta-Analysis of Nature Walk as an Intervention for Anxiety and Depression. *Journal of Clinical Medicine*, *11*(6), 1731. https://doi.org/10.3390/jcm11061731

Greenland, S., Pearl, J., & Robins, J. M. (1999). Causal diagrams for epidemiologic research. *Epidemiology*, 37-48. https://doi.org/www.jstor.org/stable/3702180

Guèvremont, A., Findlay, L., & Kohen, D. (2008). Organized extracurricular activities of Canadian children and youth. *Health reports*, *19*(3), 65.

Haase, D., Kabisch, S., Haase, A., Andersson, E., Banzhaf, E., Baró, F., Brenck, M., Fischer, L. K., Frantzeskaki, N., & Kabisch, N. (2017). Greening cities–To be socially inclusive? About the alleged paradox of society and ecology in cities. *Habitat international*, *64*, 41-48. https://doi.org/10.1016/j.habitatint.2017.04.005

Hajat, A., MacLehose, R. F., Rosofsky, A., Walker, K. D., & Clougherty, J. E. (2021). Confounding by socioeconomic status in epidemiological studies of air pollution and health: challenges and opportunities. *Environ Health Perspect*, *129*(6), 065001. https://doi.org/10.1289/EHP7980

Hamada, S., & Ohta, T. (2010). Seasonal variations in the cooling effect of urban green areas on surrounding urban areas. *Urban forestry & urban greening*, *9*(1), 15-24. https://doi.org/10.1016/j.ufug.2009.10.002

Hartig, T. (2007). Three steps to understanding restorative environments as health resources. In *Thompson, C.W., Travlou, P. (Eds.), Open Space: People Space.* (pp. 163–179).

Hartig, T., & Kahn Jr, P. H. (2016). Living in cities, naturally. *Science of the Total Environment*, *352*(6288), 938-940. https://doi.org/10.1126/science.aaf3759

Hartig, T., Mitchell, R., De Vries, S., & Frumkin, H. (2014). Nature and health. *Annual Review of Public Health*, *35*, 207-228. https://doi.org/10.1146/annurev-publhealth-032013-182443

Henson, P., Pearson, J. F., Keshavan, M., & Torous, J. (2020). Impact of dynamic greenspace exposure on symptomatology in individuals with schizophrenia. *PloS one*, *15*(9), e0238498. https://doi.org/10.1371/journal.pone.0238498

Hipp, J. R., & Wickes, R. (2017). Violence in urban neighborhoods: A longitudinal study of collective efficacy and violent crime. *Journal of Quantitative Criminology*, *33*, 783-808. https://doi.org/10.1007/s10940-016-9311-z

Hirabayashi, S., & Nowak, D. J. (2016). Comprehensive national database of tree effects on air quality and human health in the United States. *Environmental Pollution*, *215*, 48-57. https://doi.org/10.1016/j.envpol.2016.04.068

Hirsch, J. K., & Cukrowicz, K. C. (2014). Suicide in rural areas: An updated review of the literature. *Journal of Rural Mental Health*, *38*(2), 65. https://doi.org/10.1037/rmh0000018

Hoffimann, E., Barros, H., & Ribeiro, A. I. (2017). Socioeconomic inequalities in green space quality and accessibility—Evidence from a Southern European city. *Int J Environ Res Public Health*, *14*(8), 916. https://doi.org/10.3390/ijerph14080916

Holman, S., Steinberg, R., Schaffer, A., Fiksenbaum, L., & Sinyor, M. (2023). The association of social, economic, and health-related variables with suicidal and/or self-harm thoughts in individuals admitted to a psychiatric inpatient unit during the COVID-19 pandemic: An

exploratory study. *Psychiatry Research*, *319*, 114998. https://doi.org/10.1016/j.psychres.2022.114998

Houlden, V., Weich, S., Porto de Albuquerque, J., Jarvis, S., & Rees, K. (2018). The relationship between greenspace and the mental wellbeing of adults: A systematic review. *PloS One*, *13*(9), e0203000. https://doi.org/10.1371/journal.pone.0203000

Hystad, P., Payette, Y., Noisel, N., & Boileau, C. (2019). Green space associations with mental health and cognitive function: Results from the Quebec CARTaGENE cohort. *Environmental Epidemiology*, *3*(1), e040. https://doi.org/10.1097/EE9.0000000000000040

Jablensky, A. (2002). Research methods in psychiatric epidemiology: an overview*. *Australian and New Zealand Journal of Psychiatry*, *36*(3), 297-310. https://doi.org/10.1046/j.1440-1614.2002.01035.x

Jager, K., Zoccali, C., Macleod, A., & Dekker, F. (2008). Confounding: what it is and how to deal with it. *Kidney international*, *73*(3), 256-260. https://doi.org/10.1038/sj.ki.5002650

James, J. J., Christiana, R. W., & Battista, R. A. (2019). A historical and critical analysis of park prescriptions. *Journal of Leisure Research*, *50*(4), 311-329. https://doi.org/10.1080/00222216.2019.1617647

James, P., Banay, R. F., Hart, J. E., & Laden, F. (2015). A review of the health benefits of greenness. *Current Epidemiology Reports*, *2*(2), 131-142. https://doi.org/10.1007/s40471-015-0043-7

Jansson, M., Fors, H., Lindgren, T., & Wiström, B. (2013). Perceived personal safety in relation to urban woodland vegetation–A review. *Urban forestry & urban greening*, *12*(2), 127-133. https://doi.org/10.1016/j.ufug.2013.01.005

Jarvis, I., Gergel, S., Koehoorn, M., & van den Bosch, M. (2020). Greenspace access does not correspond to nature exposure: Measures of urban natural space with implications for health research. *Landscape and Urban Planning*, *194*, 103686. https://doi.org/10.1016/j.landurbplan.2019.103686

Jennings, V., & Bamkole, O. (2019). The relationship between social cohesion and urban green space: An avenue for health promotion. *Int J Environ Res Public Health*, *16*(3), 452. https://doi.org/10.3390/ijerph16030452

Jiang, W., Stickley, A., & Ueda, M. (2021). Green space and suicide mortality in Japan: An ecological study. *Social Science & Medicine*, *282*, 114137. https://doi.org/10.1016/j.socscimed.2021.114137

Jim, C. Y., & Shan, X. (2013). Socioeconomic effect on perception of urban green spaces in Guangzhou, China. *Cities*, *31*, 123-131. https://doi.org/10.1016/j.cities.2012.06.017

Jimenez, M. P., Elliott, E. G., DeVille, N. V., Laden, F., Hart, J. E., Weuve, J., Grodstein, F., & James, P. (2022). Residential green space and cognitive function in a large cohort of middle-aged women. *JAMA Network Open*, *5*(4), e229306-e229306. https://doi.org/jamanetworkopen.2022.9306

Jones, A., Hillsdon, M., & Coombes, E. (2009). Greenspace access, use, and physical activity: Understanding the effects of area deprivation. *Preventive medicine*, *49*(6), 500-505. https://doi.org/10.1016/j.ypmed.2009.10.012

Jones, K. R. (2018). 'The Lungs of the City': Green Space, Public Health and Bodily Metaphor in the Landscape of Urban Park History. *Environment and History*, *24*(1), 39-58. https://doi.org/10.3197/096734018X15137949591837

Kabisch, N. (2019). The influence of socio-economic and socio-demographic factors in the association between urban green space and health. In *Biodiversity and health in the face of climate change* (pp. 91-119).

Kaplan, R., & Kaplan, S. (1989). *The experience of nature: A psychological perspective*. Cambridge university press.

Kaplan, S. (1995). The restorative benefits of nature: Toward an integrative framework. *Journal of Environmental Psychology*, *15*(3), 169-182. https://doi.org/10.1016/0272-4944(95)90001-2

Kavanagh, A. M., Bentley, R., Turrell, G., Broom, D. H., & Subramanian, S. (2006). Does gender modify associations between self rated health and the social and economic characteristics of local environments? *Journal of Epidemiology & Community Health*, *60*(6), 490-495. https://doi.org/10.1136/jech.2005.043562

Keller, J., Kayira, J., Chawla, L., & Rhoades, J. L. (2023). Forest Bathing Increases Adolescents' Mental Well-Being: A Mixed-Methods Study. *Int J Environ Res Public Health*, *21*(1), 8. https://doi.org/10.3390/ijerph21010008

Kephart, L. (2022). How racial residential segregation structures access and exposure to greenness and green space: A review. *Environmental Justice*, *15*(4), 204-213. https://doi.org/10.1089/env.2021.0039

Kim, K., Joyce, B. T., Nannini, D. R., Zheng, Y., Gordon-Larsen, P., Shikany, J. M., Lloyd-Jones, D. M., Hu, M., Nieuwenhuijsen, M. J., & Vaughan, D. E. (2023). Inequalities in urban greenness and epigenetic aging: Different associations by race and neighborhood socioeconomic status. *Science Advances*, *9*(26), eadf8140. https://doi.org/10.1126/sciadv.adf8140

Kivimäki, M., Batty, G. D., Pentti, J., Shipley, M. J., Sipilä, P. N., Nyberg, S. T., Suominen, S. B., Oksanen, T., Stenholm, S., & Virtanen, M. (2020). Association between socioeconomic status and the development of mental and physical health conditions in adulthood: a multi-cohort study. *The Lancet Public Health*, *5*(3), e140-e149. https://doi.org/10.1016/S2468-2667(19)30248-8

Klompmaker, J. O., Hart, J. E., Bailey, C. R., Browning, M. H. E. M., Casey, J. A., Hanley, J. R., Minson, C. T., Ogletree, S. S., Rigolon, A., Laden, F., & James, P. (2023). Racial, Ethnic, and Socioeconomic Disparities in Multiple Measures of Blue and Green Spaces in the United States. *Environ Health Perspect*, *131*(1), 017007. https://doi.org/10.1289/EHP11164

Kondo, M. C., Oyekanmi, K. O., Gibson, A., South, E. C., Bocarro, J., & Hipp, J. A. (2020). Nature prescriptions for health: A review of evidence and research opportunities. *International Journal of Environmental Research Public Health*, *17*(12), 4213. https://doi.org/10.3390/ijerph17124213

Kotera, Y., Lyons, M., Vione, K. C., & Norton, B. (2021). Effect of nature walks on depression and anxiety: a systematic review. *Sustainability*, *13*(7), 4015. https://doi.org/10.3390/su13074015

Labib, S., Lindley, S., & Huck, J. J. (2020a). Scale effects in remotely sensed greenspace metrics and how to mitigate them for environmental health exposure assessment. *Computers, Environment Urban Systems*, *82*, 101501. https://doi.org/10.1016/j.compenvurbsys.2020.101501

Labib, S., Lindley, S., & Huck, J. J. (2020b). Spatial dimensions of the influence of urban green-blue spaces on human health: A systematic review. *Environmental Research*, *180*, 108869. https://doi.org/https://doi.org/10.1016/j.envres.2019.108869

Lachowycz, K., Jones, A. P., Page, A. S., Wheeler, B. W., & Cooper, A. R. (2012). What can global positioning systems tell us about the contribution of different types of urban greenspace to children's physical activity? *Health Place*, *18*(3), 586-594. https://doi.org/10.1016/j.healthplace.2012.01.006

Landry, S. M., & Chakraborty, J. (2009). Street trees and equity: evaluating the spatial distribution of an urban amenity. *Environment Planning A: Economy and Space*, *41*(11), 2651-2670. https://doi.org/10.1068/a41236

Larkin, A., & Hystad, P. (2019). Evaluating street view exposure measures of visible green space for health research. *Journal of exposure science & environmental epidemiology*, *29*(4), 447-456. https://doi.org/10.1038/s41370-018-0017-1

Lee, J., Park, B.-J., Tsunetsugu, Y., Kagawa, T., & Miyazaki, Y. (2009). Restorative effects of viewing real forest landscapes, based on a comparison with urban landscapes. *Scandinavian Journal of Forest Research*, *24*(3), 227-234. https://doi.org/10.1080/02827580902903341

Lei, Y., Davies, G. M., Jin, H., Tian, G., & Kim, G. (2021). Scale-dependent effects of urban greenspace on particulate matter air pollution. *Urban Forestry & Urban Greening*, *61*, 127089. https://doi.org/10.1016/j.ufug.2021.127089

Levesque, P., & Perron, P. A. (2024). *Les comportements suicidaires : portrait 2023. Québec, Bureau d'information et d'études en santé des populations*. Retrieved from https://www.inspq.qc.ca/publications/3294

Li, D., & Sullivan, W. C. (2016). Impact of views to school landscapes on recovery from stress and mental fatigue. *Landscape Urban Planning*, *148*, 149-158. https://doi.org/10.1016/j.landurbplan.2015.12.015

Liddicoat, C., Sydnor, H., Cando-Dumancela, C., Dresken, R., Liu, J., Gellie, N., Mills, J., Young, J., Weyrich, L., Hutchinson, M., Weinstein, P., & Breed, M. F. (2020). Naturally-diverse airborne environmental microbial exposures modulate the gut microbiome and may provide anxiolytic benefits in mice. *Science of the Total Environment*, *701*, 134684. https://doi.org/10.1016/j.scitotenv.2019.134684

Liu, X.-X., Ma, X.-L., Huang, W.-Z., Luo, Y.-N., He, C.-J., Zhong, X.-M., Dadvand, P., Browning, M. H., Li, L., & Zou, X.-G. (2022). Green space and cardiovascular disease: A systematic review with meta-analysis. *Environmental Pollution*, 118990. https://doi.org/10.1016/j.envpol.2022.118990

Liu, Z., Chen, X., Cui, H., Ma, Y., Gao, N., Li, X., Meng, X., Lin, H., Abudou, H., & Guo, L. (2023). Green space exposure on depression and anxiety outcomes: A meta-analysis. *Environmental Research*, 116303. https://doi.org/10.1016/j.envres.2023.116303

Loose, T., Côté, S., Malboeuf-Hurtubise, C., Beaudet, J.-P. A., Lessard, G., Chadi, N., Gauvin, L., Morin, I. O., & Geoffroy, M.-C. (2023). Protocol for the Open Sky School: a two-arm clustered randomized controlled trial to test the effectiveness of a nature-based intervention on mental health of elementary school children. *BMC Public Health*, *23*(1), 1-9. https://doi.org/10.1186/s12889-023-15033-y

Lorant, V., Deliège, D., Eaton, W., Robert, A., Philippot, P., & Ansseau, M. (2003). Socioeconomic inequalities in depression: a meta-analysis. *American journal of epidemiology*, *157*(2), 98-112. https://doi.org/10.1093/aje/kwf182

Luo, Y. N., Huang, W. Z., Liu, X. X., Markevych, I., Bloom, M. S., Zhao, T., Heinrich, J., Yang, B. Y., & Dong, G. H. (2020). Greenspace with overweight and obesity: A systematic review and meta-analysis of epidemiological studies up to 2020. *Obesity Reviews*, *21*(11), e13078. https://doi.org/10.1111/obr.13078

Ma, J., Lin, P., & Williams, J. (2023). Effectiveness of nature-based walking interventions in improving mental health in adults: a systematic review. *Current Psychology*, 1-19. https://doi.org/10.1007/s12144-023-05112-z

Manisalidis, I., Stavropoulou, E., Stavropoulos, A., & Bezirtzoglou, E. (2020). Environmental and health impacts of air pollution: a review. *Frontiers in public health*, *8*, 14. https://doi.org/10.3389/fpubh.2020.00014

Markevych, I., Schoierer, J., Hartig, T., Chudnovsky, A., Hystad, P., Dzhambov, A. M., De Vries, S., Triguero-Mas, M., Brauer, M., & Nieuwenhuijsen, M. J. (2017). Exploring pathways linking greenspace to health: Theoretical and methodological guidance. *Environmental Research*, *158*, 301-317. https://doi.org/10.1016/j.envres.2017.06.028

Markevych, I., Tesch, F., Datzmann, T., Romanos, M., Schmitt, J., & Heinrich, J. (2018). Outdoor air pollution, greenspace, and incidence of ADHD: A semi-individual study. *Sci Total Environ*, *642*, 1362-1368. https://doi.org/10.1016/j.scitotenv.2018.06.167

Marmot, M. (2013). Fair society, healthy lives. *Fair society, healthy lives*, 1-74.

Marmot, M., Friel, S., Bell, R., Houweling, T. A., & Taylor, S. (2008). Closing the gap in a generation: health equity through action on the social determinants of health. *The lancet*, *372*(9650), 1661-1669. https://doi.org/10.1016/S0140-6736(08)61690-6

Marvier, M., Kareiva, P., Felix, D., Ferrante, B. J., & Billington, M. B. (2023). The benefits of nature exposure: The need for research that better informs implementation. *Proceedings*

of the National Academy of Sciences, *120*(44), e2304126120. https://doi.org/10.1073/pnas.2304126120

Mathiarasan, S., & Hüls, A. (2021). Impact of environmental injustice on children's health—interaction between air pollution and socioeconomic status. *Int J Environ Res Public Health*, *18*(2), 795. https://doi.org/10.3390/ijerph18020795

Mavoa, S., Lucassen, M., Denny, S., Utter, J., Clark, T., & Smith, M. (2019). Natural neighbourhood environments and the emotional health of urban New Zealand adolescents. *Landscape Urban Planning*, *191*, 103638. https://doi.org/https://doi.org/10.1016/j.landurbplan.2019.103638

McClelland, H., Evans, J. J., Nowland, R., Ferguson, E., & O'Connor, R. C. (2020). Loneliness as a predictor of suicidal ideation and behaviour: a systematic review and meta-analysis of prospective studies. *Journal of Affective Disorders*, *274*, 880-896. https://doi.org/10.1016/j.jad.2020.05.004

McCormick, R. (2017). Does access to green space impact the mental well-being of children: A systematic review. *Journal of Pediatric Nursing*, *37*, 3-7. https://doi.org/10.1016/j.pedn.2017.08.027

Mears, M., Brindley, P., Jorgensen, A., Ersoy, E., & Maheswaran, R. (2019). Greenspace spatial characteristics and human health in an urban environment: An epidemiological study using landscape metrics in Sheffield, UK. *Ecological Indicators*, *106*, 105464. https://doi.org/10.1016/j.ecolind.2019.105464

Messiah, S. E., D'Agostino, E. M., Hansen, E., Mathew, M. S., Okeke, D., Nardi, M., Kardys, J., & Arheart, K. L. (2018). Longitudinal impact of a park-based afterschool healthy weight

program on modifiable cardiovascular disease risk factors in youth. *Journal of community health*, *43*, 103-116. https://doi.org/10.1007/s10900-017-0393-9

Mitchell, R. (2013). Is physical activity in natural environments better for mental health than physical activity in other environments? *Social science & medicine*, *91*, 130-134. https://doi.org/10.1016/j.socscimed.2012.04.012

Mitchell, R., & Popham, F. (2008). Effect of exposure to natural environment on health inequalities: an observational population study. *The lancet*, *372*(9650), 1655-1660.

Mizutani, J. (2018). In the backyard of segregated neighborhoods: an environmental justice case study of Louisiana. *Geo. Envtl. L. Rev.*, *31*, 363. https://doi.org/https://link-gale-com.proxy3.library.mcgill.ca/apps/doc/A583381558/LT?u=crepuq_mcgill&sid=bookmark-LT&xid=33475444

National Health Service England. (2024). *Green social prescribing*. Retrieved January 4, 2024 from https://www.england.nhs.uk/personalisedcare/social-prescribing/green-social-prescribing/

Nguyen, P.-Y., Astell-Burt, T., Rahimi-Ardabili, H., & Feng, X. (2023). Effect of nature prescriptions on cardiometabolic and mental health, and physical activity: a systematic review. *The Lancet Planetary Health*, *7*(4), e313-e328. https://doi.org/10.1016/S2542-5196(23)00025-6

Nieuwenhuijsen, M., & Khreis, H. (2019). Green Space and Health. In *Integrating Human Health into Urban and Transport Planning: A Framework* (pp. 409–423). Springer International Publishing.

Nieuwenhuijsen, M. J., Khreis, H., Triguero-Mas, M., Gascon, M., & Dadvand, P. (2017). Fifty shades of green. *Epidemiology*, *28*(1), 63-71. https://doi.org/10.1097/EDE.0000000000000549

Núñez, M.-B. F., Suzman, L. C., Maneja, R., Bach, A., Marquet, O., Anguelovski, I., & Knobel, P. (2022). Gender and sex differences in urban greenness' mental health benefits: A systematic review. *Health & Place*, *76*, 102864. https://doi.org/10.1016/j.healthplace.2022.102864

Nutsford, D., Pearson, A., & Kingham, S. (2013). An ecological study investigating the association between access to urban green space and mental health. *Public Health*, *127*(11), 1005-1011. https://doi.org/10.1016/j.puhe.2013.08.016

Oakes, J. M. (2004). The (mis) estimation of neighborhood effects: causal inference for a practicable social epidemiology. *Social science & medicine*, *58*(10), 1929-1952. https://doi.org/10.1016/j.socscimed.2003.08.004

Orri, M., Scardera, S., Perret, L. C., Bolanis, D., Temcheff, C., Séguin, J. R., Boivin, M., Turecki, G., Tremblay, R. E., & Côté, S. M. (2020). Mental health problems and risk of suicidal ideation and attempts in adolescents. *Pediatrics*, *146*(1). https://doi.org/https://doi.org/10.1542/peds.2019-3823

Park, B.-J., Tsunetsugu, Y., Kasetani, T., Hirano, H., Kagawa, T., Sato, M., & Miyazaki, Y. (2007). Physiological effects of shinrin-yoku (taking in the atmosphere of the forest)—using salivary cortisol and cerebral activity as indicators. *Journal of physiological anthropology*, *26*(2), 123-128. https://doi.org/10.2114/jpa2.26.123

Parks Canada. (2014). Connecting Canadians with nature: An investment in the well-being of our citizens. In: Parks Canada Ottawa, ON.

Pastor, M., Sadd, J., & Hipp, J. (2001). Which came first? Toxic facilities, minority move-in, and environmental justice. *Journal of urban affairs*, *23*(1), 1-21. https://doi.org/10.1111/0735-2166.00072

Patel, V., Saxena, S., Lund, C., Thornicroft, G., Baingana, F., Bolton, P., Chisholm, D., Collins, P. Y., Cooper, J. L., & Eaton, J. (2018). The Lancet Commission on global mental health and sustainable development. *The lancet*, *392*(10157), 1553-1598. https://doi.org/10.1016/S0140-6736(18)31612-X

Patil, R. R. (2014). Urbanization as a determinant of health: a socioepidemiological perspective. *Social work in public health*, *29*(4), 335-341. https://doi.org/10.1080/19371918.2013.821360

Pettorelli, N. (2013). NDVI from A to Z. In *The Normalized Difference Vegetation Index* (pp. 30-43). Oxford University Press. https://doi.org/10.1093/acprof:osobl/9780199693160.001.0001

Phelan, P. E., Kaloush, K., Miner, M., Golden, J., Phelan, B., Silva III, H., & Taylor, R. A. (2015). Urban heat island: mechanisms, implications, and possible remedies. *Annual Review of Environment and Resources*, *40*, 285-307. https://doi.org/10.1146/annurev-environ-102014-021155

Piché, G., Huỳnh, C., & Villatte, A. (2019). Physical activity and child depressive symptoms: Findings from the QLSCD. *Canadian Journal of Behavioural Science / Revue canadienne des sciences du comportement*, *51*(2), 114-121. https://doi.org/10.1037/cbs0000120

Plümecke, T., Wilopo, C. S., & Naguib, T. (2023). Effects of racial profiling: The subjectivation of discriminatory police practices. *Ethnic and Racial Studies*, *46*(5), 811-831. https://doi.org/10.1080/01419870.2022.2077124

Prescri-Nature. (2024). *Une prescription qui vaut la peine d'être suivie*. https://www.prescri-nature.ca

Pretty, J., Peacock, J., Sellens, M., & Griffin, M. (2005). The mental and physical health outcomes of green exercise. *International journal of environmental health research*, *15*(5), 319-337. https://doi.org/10.1080/09603120500155963

Rahimi, E., Barghjelveh, S., & Dong, P. (2022). A comparison of discrete and continuous metrics for measuring landscape changes. *Journal of the Indian Society of Remote Sensing*, *50*(7), 1257-1273. https://doi.org/10.1007/s12524-022-01526-7

Reece, R., Bornioli, A., Bray, I., Newbutt, N., Satenstein, D., & Alford, C. (2022). Exposure to green, blue and historic environments and mental well-being: a comparison between virtual reality head-mounted display and flat screen exposure. *Int J Environ Res Public Health*, *19*(15), 9457. https://doi.org/10.3390/ijerph19159457

Reed, A. C., Haldane, V., Mincer, J., McDermott, E., & Rawlyk, B. (2021). Nature prescribing in Canada: a trainee led discussion on implementation and educational opportunities. *The Journal of Climate Change and Health*(4), 100040. https://doi.org/10.1016/j.joclim.2021.100011

Reid, C. E., Kubzansky, L. D., Li, J., Shmool, J. L., & Clougherty, J. E. (2018). It's not easy assessing greenness: a comparison of NDVI datasets and neighborhood types and their associations with self-rated health in New York City. *Health & place*, *54*, 92-101. https://doi.org/10.1016/j.healthplace.2018.09.005

Reuben, A., Arseneault, L., Belsky, D. W., Caspi, A., Fisher, H. L., Houts, R. M., Moffitt, T. E., & Odgers, C. (2019). Residential neighborhood greenery and children's cognitive development. *Social Science Medicine*, *230*, 271-279. https://doi.org/10.1016/j.socscimed.2019.04.029

Richardson, E. A., & Mitchell, R. (2010). Gender differences in relationships between urban green space and health in the United Kingdom. *Social science & medicine*, *71*(3), 568-575. https://doi.org/10.1016/j.socscimed.2010.04.015

Richardson, E. A., Mitchell, R., Hartig, T., De Vries, S., Astell-Burt, T., & Frumkin, H. (2011). Green cities and health: a question of scale? *J Epidemiol Community Health*. https://doi.org/10.1136/jech.2011.137240

Richardson, E. A., Pearce, J., Mitchell, R., & Kingham, S. (2013). Role of physical activity in the relationship between urban green space and health. *Public Health*, *127*(4), 318-324. https://doi.org/10.1016/j.puhe.2013.01.004

Richardson, E. A., Pearce, J., Shortt, N. K., & Mitchell, R. (2017). The role of public and private natural space in children's social, emotional and behavioural development in Scotland: A longitudinal study. *Environmental Research*, *158*, 729-736. https://doi.org/10.1016/j.envres.2017.07.038

Richardson, M., Cormack, A., McRobert, L., & Underhill, R. (2016). 30 days wild: Development and evaluation of a large-scale nature engagement campaign to improve well-being. *PloS One*, *11*(2), e0149777. https://doi.org/https://doi.org/10.1371/journal.pone.0149777

Rigolon, A. (2016). A complex landscape of inequity in access to urban parks: A literature review. *Landscape and Urban Planning*, *153*, 160-169. https://doi.org/10.1016/j.landurbplan.2016.05.017

Riley, A. R. (2018). Neighborhood disadvantage, residential segregation, and beyond—lessons for studying structural racism and health. *Journal of racial and ethnic health disparities*, *5*, 357-365. https://doi.org/10.1007/s40615-017-0378-5

Riva, G., Waterworth, J. A., Waterworth, E. L., & Mantovani, F. (2011). From intention to action: The role of presence. *New Ideas in Psychology*, *29*(1), 24-37. https://doi.org/10.1016/j.newideapsych.2009.11.002

Roberts, S., Arseneault, L., Barratt, B., Beevers, S., Danese, A., Odgers, C. L., Moffitt, T. E., Reuben, A., Kelly, F. J., & Fisher, H. L. (2019). Exploration of NO2 and PM2. 5 air pollution and mental health problems using high-resolution data in London-based children from a UK longitudinal cohort study. *Psychiatry Research*, *272*, 8-17. https://doi.org/10.1016/j.psychres.2018.12.050

Robinson, T., Robertson, N., Curtis, F., Darko, N., & Jones, C. R. (2022). Examining psychosocial and economic barriers to green space access for racialised individuals and families: a narrative literature review of the evidence to date. *Int J Environ Res Public Health*, *20*(1), 745. https://doi.org/https://doi.org/10.3390/ijerph20010745

Roe, J., Aspinall, P. A., & Ward Thompson, C. (2016). Understanding relationships between health, ethnicity, place and the role of urban green space in deprived urban communities. *Int J Environ Res Public Health*, *13*(7), 681. https://doi.org/10.3390/ijerph13070681

Rosenberg, M. (2017). Health geography III: Old ideas, new ideas or new determinisms? *Progress in Human Geography*, *41*(6), 832-842. https://doi.org/10.1177/0309132516670054

Rydin, Y., Bleahu, A., Davies, M., Dávila, J. D., Friel, S., De Grandis, G., Groce, N., Hallal, P. C., Hamilton, I., & Howden-Chapman, P. (2012). Shaping cities for health: complexity

and the planning of urban environments in the 21st century. *The lancet*, *379*(9831), 2079-2108. https://doi.org/10.1016/S0140-6736(12)60435-8

Sakhvidi, M. J. Z., Knobel, P., Bauwelinck, M., de Keijzer, C., Boll, L. M., Spano, G., Ubalde-Lopez, M., Sanesi, G., Mehrparvar, A. H., & Jacquemin, B. (2022). Greenspace exposure and children behavior: A systematic review. *Science of the Total Environment*, 153608. https://doi.org/https://doi.org/10.1016/j.scitotenv.2022.153608

Sampson, R. J., Morenoff, J. D., & Gannon-Rowley, T. (2002). Assessing "neighborhood effects": Social processes and new directions in research. *Annual review of sociology*, *28*(1), 443-478. https://doi.org/10.1146/annurev.soc.28.110601.141114

Santamouris, M., Ban-Weiss, G., Osmond, P., Paolini, R., Synnefa, A., Cartalis, C., Muscio, A., Zinzi, M., Morakinyo, T. E., & Edward, N. (2018). Progress in urban greenery mitigation science–assessment methodologies advanced technologies and impact on cities. *Journal of Civil Engineering and Management*, *24*(8), 638-671. https://doi.org/10.3846/jcem.2018.6604

Seaman, P. J., Jones, R., & Ellaway, A. (2010). It's not just about the park, it's about integration too: why people choose to use or not use urban greenspaces. *International Journal of Behavioral Nutrition and Physical Activity*, *7*(1), 1-9. https://doi.org/10.1186/1479-5868-7-78

Shen, Y.-S., Lung, S.-C. C., & Cui, S. (2022). Exploring multiple pathways and mediation effects of urban environmental factors for suicide prevention. *Environmental Pollution*, *294*, 118642. https://doi.org/10.1016/j.envpol.2021.118642

Sillman, D., Rigolon, A., Browning, M. H., & McAnirlin, O. (2022). Do sex and gender modify the association between green space and physical health? A systematic review. *Environmental Research*, *209*, 112869. https://doi.org/10.1016/j.envres.2022.112869

Skår, M., & Krogh, E. (2009). Changes in children's nature-based experiences near home: from spontaneous play to adult-controlled, planned and organised activities. *Children's Geographies*, *7*(3), 339-354. https://doi.org/10.1080/14733280903024506

Solmi, M., Radua, J., Olivola, M., Croce, E., Soardo, L., Salazar de Pablo, G., Il Shin, J., Kirkbride, J. B., Jones, P., & Kim, J. H. (2022). Age at onset of mental disorders worldwide: large-scale meta-analysis of 192 epidemiological studies. *Molecular Psychiatry*, *27*(1), 281-295. https://doi.org/10.1038/s41380-021-01161-7

Sonti, N. F., Campbell, L. K., Svendsen, E. S., Johnson, M. L., & Auyeung, D. N. (2020). Fear and fascination: Use and perceptions of New York City's forests, wetlands, and landscaped park areas. *Urban Forestry & Urban Greening*, *49*, 126601. https://doi.org/10.1016/j.ufug.2020.126601

Sprague, N. L., Bancalari, P., Karim, W., & Siddiq, S. (2022). Growing up green: A systematic review of the influence of greenspace on youth development and health outcomes. *Journal of exposure science & environmental epidemiology*, *32*(5), 660-681. https://doi.org/10.1038/s41370-022-00445-6

Sreetheran, M., & Van Den Bosch, C. C. K. (2014). A socio-ecological exploration of fear of crime in urban green spaces–A systematic review. *Urban Forestry & Urban Greening*, *13*(1), 1-18. https://doi.org/10.1016/j.ufug.2013.11.006

Stafford, M., Cummins, S., Macintyre, S., Ellaway, A., & Marmot, M. (2005). Gender differences in the associations between health and neighbourhood environment. *Social science & medicine*, *60*(8), 1681-1692. https://doi.org/10.1016/j.socscimed.2004.08.028

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. *Journal of Toxicology and Environmental Health, Part B*, *21*(4), 227-268. https://doi.org/10.1080/10937404.2018.1505571

Stewart-Brown, S., Tennant, A., Tennant, R., Platt, S., Parkinson, J., & Weich, S. (2009). Internal construct validity of the Warwick-Edinburgh mental well-being scale (WEMWBS): a Rasch analysis using data from the Scottish health education population survey. *Health and quality of life outcomes*, *7*(1), 1-8. https://doi.org/10.1186/1477-7525-7-15

Sturm, J., Plöderl, M., Fartacek, C., Kralovec, K., Neunhäuserer, D., Niederseer, D., Hitzl, W., Niebauer, J., Schiepek, G., & Fartacek, R. (2012). Physical exercise through mountain hiking in high-risk suicide patients. A randomized crossover trial. *Acta Psychiatrica Scandinavica*, *126*(6), 467-475. https://doi.org/https://doi.org/10.1111/1600-0447.2012.01860.x

Su, J. G., Dadvand, P., Nieuwenhuijsen, M. J., Bartoll, X., & Jerrett, M. (2019). Associations of green space metrics with health and behavior outcomes at different buffer sizes and remote sensing sensor resolutions. *Environ Int*, *126*, 162-170. https://doi.org/10.1016/j.envint.2019.02.008

Sugiyama, T., Leslie, E., Giles-Corti, B., & Owen, N. (2008). Associations of neighbourhood greenness with physical and mental health: do walking, social coherence and local social

interaction explain the relationships? *Journal of epidemiology and community health*, *62*(5), ARTN e9. https://doi.org/10.1136/jech.2007.064287

Sundermann, M., Chielli, D., & Spell, S. (2023). Nature As Medicine: The 7th (Unofficial) Pillar of Lifestyle Medicine. *American Journal of Lifestyle Medicine*, 15598276231174863. https://doi.org/10.1177/15598276231174863

Suttorp, M. M., Siegerink, B., Jager, K. J., Zoccali, C., & Dekker, F. W. (2015). Graphical presentation of confounding in directed acyclic graphs. *Nephrology Dialysis Transplantation*, *30*(9), 1418-1423. https://doi.org/10.1093/ndt/gfu325

Taylor, L., & Hochuli, D. F. (2017). Defining greenspace: Multiple uses across multiple disciplines. *Landscape Urban Planning*, *158*, 25-38. https://doi.org/10.1016/j.landurbplan.2016.09.024

Tennant, P. W., Murray, E. J., Arnold, K. F., Berrie, L., Fox, M. P., Gadd, S. C., Harrison, W. J., Keeble, C., Ranker, L. R., & Textor, J. (2021). Use of directed acyclic graphs (DAGs) to identify confounders in applied health research: review and recommendations. *International journal of epidemiology*, *50*(2), 620-632. https://doi.org/10.1093/ije/dyaa213

Thompson Coon, J., Boddy, K., Stein, K., Whear, R., Barton, J., & Depledge, M. H. (2011). Does participating in physical activity in outdoor natural environments have a greater effect on physical and mental wellbeing than physical activity indoors? A systematic review. *Environmental science & technology*, *45*(5), 1761-1772. https://doi.org/10.1021/es102947t

Thompson, C. W., Roe, J., Aspinall, P., Mitchell, R., Clow, A., & Miller, D. (2012). More green space is linked to less stress in deprived communities: Evidence from salivary cortisol

patterns. *Landscape and urban planning*, *105*(3), 221-229. https://doi.org/10.1016/j.landurbplan.2011.12.015

Thygesen, M., Engemann, K., Holst, G. J., Hansen, B., Geels, C., Brandt, J., Pedersen, C. B., & Dalsgaard, S. (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. https://doi.org/10.1289/EHP6729

Tran, I., Sabol, O., & Mote, J. (2022). The relationship between greenspace exposure and psychopathology symptoms: A systematic review. *Biological Psychiatry Global Open Science*, *2*(3), 206-222. https://doi.org/10.1016/j.bpsgos.2022.01.004

Tudor, K. (1996). Mental health In *Mental health promotion: paradigms and practice* (pp. 21-31). Routledge. https://doi.org/10.1007/BF02573948

Turecki, G., & Brent, D. A. (2016). Suicide and suicidal behaviour. *The Lancet Psychiatry*, *387*(10024), 1227-1239. https://doi.org/https://doi.org/10.1016/S0140-6736(15)00234-2

Turner, M. G. (1990). Spatial and temporal analysis of landscape patterns. *Landscape ecology*, *4*, 21-30. https://doi.org/10.1641/0006-3568(2004)054[0585:GUATSO]2.0.CO;2

Turner, W. R., Nakamura, T., & Dinetti, M. (2004). Global urbanization and the separation of humans from nature. *Bioscience*, *54*(6), 585-590. https://doi.org/10.1002/wps.20436

Uher, R., & Zwicker, A. (2017). Etiology in psychiatry: embracing the reality of poly-gene-environmental causation of mental illness. *World Psychiatry*, *16*(2), 121-129. https://doi.org/10.1002/wps.20436

Ulrich, R. S. (1983). Aesthetic and affective response to natural environment. In *Human Behaviour and Environment* (Vol. 6 pp. 85-125). Springer. https://doi.org/10.1007/978-1-4613-3539-9_4

Ulrich, R. S. (1993). Biophilia, biophobia and natural landscapes. In *The Biophilia Hypothesis* (pp. 73–137). Island Press.

Ulrich, R. S., Simons, R. F., Losito, B. D., Fiorito, E., Miles, M. A., & Zelson, M. (1991). Stress recovery during exposure to natural and urban environments. *Journal of Environmental Psychology*, *11*(3), 201-230. https://doi.org/10.1016/S0272-4944(05)80184-7

Uuemaa, E., Antrop, M., Roosaare, J., Marja, R., & Mander, Ü. (2009). Landscape metrics and indices: an overview of their use in landscape research. *Living reviews in landscape research*, *3*(1), 1-28. https://doi.org/http://hdl.handle.net/1854/LU-695518

Uuemaa, E., Mander, Ü., & Marja, R. (2013). Trends in the use of landscape spatial metrics as landscape indicators: A review. *Ecological Indicators*, *28*, 100-106. https://doi.org/10.1016/j.ecolind.2012.07.018

Van den Berg, M., Wendel-Vos, W., van Poppel, M., Kemper, H., van Mechelen, W., & Maas, J. (2015). Health benefits of green spaces in the living environment: A systematic review of epidemiological studies. *Urban Forestry Urban Greening*, *14*(4), 806-816. https://doi.org/10.1016/j.ufug.2015.07.008

Vanaken, G.-J., & Danckaerts, M. (2018). Impact of green space exposure on children's and adolescents' mental health: A systematic review. *International Journal of Environmental Research Public Health*, *15*(12), 2668. https://doi.org/10.3390/ijerph15122668

VanderWeele, T. J. (2019). Principles of confounder selection. *European journal of epidemiology*, *34*, 211-219. https://doi.org/10.1007/s10654-019-00494-6

Vaughan, K. B., Kaczynski, A. T., Wilhelm Stanis, S. A., Besenyi, G. M., Bergstrom, R., & Heinrich, K. M. (2013). Exploring the distribution of park availability, features, and quality across Kansas City, Missouri by income and race/ethnicity: An environmental

justice investigation. *Annals of behavioral medicine*, *45*(suppl_1), S28-S38. https://doi.org/10.1007/s12160-012-9425-y

Vella-Brodrick, D. A., & Gilowska, K. (2022). Effects of nature (greenspace) on cognitive functioning in school children and adolescents: A systematic review. *Educational Psychology Review*, *34*(3), 1217-1254. https://doi.org/10.1007/s10648-022-09658-5

Ventriglio, A., Torales, J., Castaldelli-Maia, J. M., De Berardis, D., & Bhugra, D. (2021). Urbanization and emerging mental health issues. *CNS spectrums*, *26*(1), 43-50. https://doi.org/10.1017/S1092852920001236

Vlahov, D., & Galea, S. (2003). Urban health: a new discipline. *The Lancet*, *362*(9390), 1091-1092. https://doi.org/10.1016/S0140-6736(03)14499-6

Von Hertzen, L., Hanski, I., & Haahtela, T. (2011). Natural immunity: biodiversity loss and inflammatory diseases are two global megatrends that might be related. *EMBO reports*, *12*(11), 1089-1093. https://doi.org/10.1038/embor.2011.195

Voogt, J. A., & Oke, T. R. (2003). Thermal remote sensing of urban climates. *Remote Sensing of Environment*, *86*(3), 370-384. https://doi.org/10.1016/S0034-4257(03)00079-8

Wallner, P., Kundi, M., Arnberger, A., Eder, R., Allex, B., Weitensfelder, L., & Hutter, H.-P. (2018). Reloading pupils' batteries: Impact of green spaces on cognition and wellbeing. *Int J Environ Res Public Health*, *15*(6), 1205. https://doi.org/10.3390/ijerph15061205

Wang, C., Sheng, Y., Wang, J., Wang, Y., Wang, P., & Huang, L. (2022). Air pollution and human health: Investigating the moderating effect of the built environment. *Remote Sensing*, *14*(15), 3703. https://doi.org/10.3390/rs14153703

Wang, R., Feng, Z., Pearce, J., Zhou, S., Zhang, L., & Liu, Y. (2021). Dynamic greenspace exposure and residents' mental health in Guangzhou, China: From over-head to eye-level

perspective, from quantity to quality. *Landscape and Urban Planning*, *215*, 104230. https://doi.org/10.1016/j.landurbplan.2021.104230

Watkins-Martin, K., Bolanis, D., Devantoy, S. R., Pennestri, M.-H., Malboeuf-Hurtubise, C., Philippe, F. L., Guindon, J., Gouin, J.-P., Ouellet-Morin, I., & Geoffroy, M.-C. (2021). The effects of walking in nature on negative and positive affect in adult psychiatric outpatients with major depressive disorder: A randomized-controlled study. *medRxiv*. https://doi.org/10.1101/2021.11.25.21266872

Wen, Y., Yan, Q., Pan, Y., Gu, X., & Liu, Y. (2019). Medical empirical research on forest bathing (Shinrin-yoku): a systematic review. *Environmental Health Preventive Medicine*, *24*(1), 1-21. https://doi.org/10.1186/s12199-019-0822-8

White, S. C. (2008). But what is wellbeing? A framework for analysis in social and development policy and practice. https://people.bath.ac.uk/ecsscw/But_what_is_Wellbeing.pdf

Whiteford, H. A., Degenhardt, L., Rehm, J., Baxter, A. J., Ferrari, A. J., Erskine, H. E., Charlson, F. J., Norman, R. E., Flaxman, A. D., & Johns, N. (2013). Global burden of disease attributable to mental and substance use disorders: findings from the Global Burden of Disease Study 2010. *The lancet*, *382*(9904), 1575-1586. https://doi.org/10.1016/S0140-6736(13)61611-6

Wilson, E. O. (1984). *Biophilia*. Harvard University Press.

Wolch, J. R., Byrne, J., & Newell, J. P. (2014). Urban green space, public health, and environmental justice: The challenge of making cities 'just green enough'. *Landscape and urban planning*, *125*, 234-244. https://doi.org/10.1016/j.landurbplan.2014.01.017

World Health Organization. (2017a). *Suicide Data*. https://www.who.int/news-room/fact-sheets/detail/suicide

World Health Organization. (2017b). *Urban green spaces: a brief for action*. Regional Office for Europe,. https://doi.org/https://iris.who.int/handle/10665/344116

World Health Organization. (2021). *Comprehensive mental health action plan 2013–2030*. https://iris.who.int/bitstream/handle/10665/345301/9789240031029-eng.pdf,

World Health Organization. (2022). *World mental health report: transforming mental health for all*. https://www.who.int/publications/i/item/9789240049338

World Health Organization Centre for Health Development. (2010). *Hidden cities: unmasking and overcoming health inequities in urban settings*.

Ye, T., Yu, P., Wen, B., Yang, Z., Huang, W., Guo, Y., Abramson, M. J., & Li, S. (2022). Greenspace and health outcomes in children and adolescents: A systematic review. *Environmental Pollution*, 120193. https://doi.org/10.1016/j.envpol.2022.120193

Yeo, N., White, M., Alcock, I., Garside, R., Dean, S., Smalley, A., & Gatersleben, B. (2020). What is the best way of delivering virtual nature for improving mood? An experimental comparison of high definition TV, 360 video, and computer generated virtual reality. *Journal of Environmental Psychology*, *72*, 101500. https://doi.org/10.1016/j.jenvp.2020.101500

Yuan, M., Yin, C., Sun, Y., & Chen, W. (2019). Examining the associations between urban built environment and noise pollution in high-density high-rise urban areas: A case study in Wuhan, China. *Sustainable Cities and Society*, *50*, 101678. https://doi.org/10.1016/j.scs.2019.101678

Zhang, J., Yu, Z., Zhao, B., Sun, R., & Vejre, H. (2020). Links between green space and public health: a bibliometric review of global research trends and future prospects from 1901 to

2019. *Environmental Research Letters*, *15*(6), 063001. https://doi.org/10.1088/1748-9326/ab7f64

Zhang, K., Chen, T.-H., & Begley, C. E. (2015). Impact of the 2011 heat wave on mortality and emergency department visits in Houston, Texas. *Environmental Health*, *14*(1), 1-7. https://doi.org/10.1186/1476-069X-14-11

Zhang, R., Zhang, C.-Q., & Rhodes, R. E. (2021). The pathways linking objectively-measured greenspace exposure and mental health: A systematic review of observational studies. *Environmental Research*, *198*, 111233. https://doi.org/10.1016/j.envres.2021.111233

Zhang, Y., Mavoa, S., Zhao, J., Raphael, D., & Smith, M. (2020). The association between green space and adolescents' mental well-being: a systematic review. *International Journal of Environmental Research Public Health*, *17*(18), 6640. https://doi.org/10.3390/ijerph17186640

Zhang, Y.-D., Fan, S.-J., Zhang, Z., Li, J.-X., Liu, X.-X., Hu, L.-X., Knibbs, L. D., Dadvand, P., Jalaludin, B., & Browning, M. H. (2023). Association between Residential Greenness and Human Microbiota: Evidence from Multiple Countries. *Environ Health Perspect*, *131*(8), 087010. https://doi.org/10.1289/EHP12186

Zhao, Y., Bao, W.-W., Yang, B.-Y., Liang, J.-H., Gui, Z.-H., Huang, S., Chen, Y.-C., Dong, G.-H., & Chen, Y.-J. (2022). Association between greenspace and blood pressure: A systematic review and meta-analysis. *Science of the Total Environment*, *817*, 152513. https://doi.org/10.1016/j.scitotenv.2021.152513

Zhou, P., Sun, S., Chen, T., Pan, Y., Xu, W., & Zhang, H. (2022). Impacts of Social Inequality, Air Pollution, Rural–Urban Divides, and Insufficient Green Space on Residents' Health

in China: Insight from Chinese General Social Survey Data Analysis. *Int J Environ Res Public Health*, *19*(21), 14225. https://doi.org/10.3390/ijerph192114225

Zijlema, W. L., Triguero-Mas, M., Smith, G., Cirach, M., Martinez, D., Dadvand, P., Gascon, M., Jones, M., Gidlow, C., & Hurst, G. (2017). The relationship between natural outdoor environments and cognitive functioning and its mediators. *Environmental Research*, *155*, 268-275. https://doi.org/10.1016/j.envres.2017.02.017