

Neighbourhood Green and Blue Space and Child Health

Diogo Bernardo de Lacerda Queiroz e Almeida (Candidato)

Ana Isabel Correia Ribeiro (Orientadora)

(EPIUnit - Instituto de Saúde Pública da Universidade do Porto, Laboratório para a Investigação Integrativa e Translacional em Saúde Populacional (ITR), Porto, Portugal & Departamento de Geografia, Faculdade de Letras da Universidade do Porto, Centro de Estudos em Geografia e Ordenamento do Território (CEGOT))

José Henrique Dias Pinto de Barros (Coorientador)

(EPIUnit - Instituto de Saúde Pública da Universidade do Porto, Laboratório para a Investigação Integrativa e Translacional em Saúde Populacional (ITR), Porto, Portugal & Departamento de Ciências da Saúde Pública e Forenses e Educação Médica, Faculdade de Medicina da Universidade do Porto)



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Throughout the preparation of this PhD thesis, I contributed to defining the research hypotheses and objectives addressed in each article, as well as analysing and interpreting the data for Publications I and III. I was also involved in the data collection process for Publication IV, as well as in the curation, analysis, and interpretation of the data. I was responsible for drafting the first version of all manuscripts and served as the first author, actively contributing to the preparation of the final versions of all publications.

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“In nature, a child finds freedom, fantasy, and privacy: a place distant from the
adult world, a separate peace.”

Richard Louv, Last Child in the Woods

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No man is an island,
Entire of itself;
Every man is a piece of the continent,
A part of the main.

If a clod be washed away by the sea,
Europe is the less,
As well as if a promontory were:
As well as if a manor of thy friend's
Or of thine own were.

Any man's death diminishes me,
Because I am involved in mankind.
And therefore never send to know for whom the bell tolls;
It tolls for thee.

John Donne, Meditation XVII (1624)

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Abbreviations

ADHD – Attention Deficit Hyperactivity Disorder

BMI – Body Mass Index

DAG – Directed Acyclic Graph

DOHaD – Developmental Origins of Health and Disease

EDI – European Deprivation Index

FEF_{25–75%} – Forced Expiratory Flow Between 25% and 75% of Forced Vital Capacity

FEV₁ – Forced Expiratory Volume at the First Second

FVC – Forced Vital Capacity

G21 – Generation XXI Birth Cohort

GIS – Geographic Information System

GLI – Global Lung Function Initiative

HADS – Hospital Anxiety and Depression Scale

IQ – Intelligence Quotient

ISCED – International Standard Classification of Education

LAI – Leaf Area Index

MODIS – Moderate Resolution Imaging Spectroradiometer

NDVI – Normalized Difference Vegetation Index

NO₂ – Nitrogen Dioxide

OLI – Operational Land Imager

OR – Odds Ratio

PM_{2.5} – Particulate Matter with a Diameter of 2.5 µm or Less

SEM – Structural Equation Modelling

SES – Socioeconomic Status

TM – Thematic Mapper

UGS – Urban Green Space

UNICEF – United Nations International Children's Emergency Fund

WISC-III – Wechsler Intelligence Scale for Children – Third Edition

WHO – World Health Organization

Abstract

Introduction: Krieger's eco-social model highlights that health emerges from dynamic interactions across multiple levels and that these influences are embodied over the life course. Urban health studies further reveal that cities concentrate both opportunities and risks: access to healthcare and education coexists with exposures to pollution, heat islands, and stark inequalities across neighbourhoods. Green and blue spaces play a unique role in this landscape. Research shows that contact with these spaces supports resilience, empathy, curiosity, and social interaction, while also buffering environmental hazards such as air pollution, noise, and heat. They improve air quality, cool urban heat, promote physical activity, reduce stress, and foster social cohesion. Studies increasingly link them to lower mortality, better cardiovascular and respiratory health, improved mental well-being, and enhanced cognitive outcomes. For children, these benefits are especially critical given their developmental sensitivity and the long-term imprint of early-life exposures. Despite growing evidence, important knowledge gaps remain. Most studies are still cross-sectional, limiting understanding of sensitive developmental windows and cumulative life-course effects. Blue spaces are comparatively underexplored, and methodological inconsistencies persist in how exposure is defined and measured.

Objectives: The main research question guiding this PhD dissertation is: Do neighbourhood green and blue spaces influence children's health across development? To address this, the thesis pursues four specific aims: (I) examine the association between residential and school green and blue spaces and children's intelligence; (II) investigate the influence of green and blue space exposure on children's respiratory health and lung function trajectories; (III) assess the relationship between surrounding greenness and behavioural problems in childhood, considering cumulative exposures across developmental stages; and (IV) explore adolescents' perceptions, experiences, and preferences regarding green spaces, with a focus on modes of use, perceived benefits, and desired features.

Methods: This thesis investigates how green and blue spaces influence children's health using three quantitative studies and one qualitative study, all nested within the Generation XXI Birth Cohort (G21) in Porto, Portugal. The G21 cohort enrolled 8647

newborns in 2005–2006 and has followed them at multiple time points with comprehensive health, sociodemographic, and environmental data collection. For the intelligence study, 3827 children who completed an intelligence assessment at age 10 were analysed. Exposure was derived from satellite-based indices (normalized difference vegetation index (NDVI)) and from accessibility measures to green and blue spaces around residential and school addresses, and intelligence by the verbal, performance, and global intelligence quotient (IQ), measured using the Wechsler Intelligence Scale for Children. Associations were estimated using mixed-effects models adjusting for sociodemographic confounders. Further adjustments were made to assess two possible mediators (physical activity, air pollution). For the respiratory study, 3278 children with lung function data at age 10 were included. Spirometry was performed using standardised protocols, with outcomes including the forced vital capacity (FVC), the forced expiratory volume at the first second (FEV₁), and the forced expiratory flow between 25% and 75% of forced vital capacity (FEF_{25–75%}). Exposure was derived from satellite-based indices (NDVI) and from accessibility measures to green and blue spaces around the residence. The exposures were modelled across multiple childhood time points to capture life course trajectories, and associations were assessed with linear regression models adjusting for sociodemographic confounders. Path analysis was used to assess two possible mediators (physical activity, air pollution). The study on behavioural problems comprised 6269 children with behavioural assessments at age 7 reported by the caretakers. Exposure was derived from satellite-based indices (NDVI, non-tree vegetated area, tree-vegetated area, and non-vegetated area). The exposures were modelled across multiple childhood time points to capture life course trajectories, and associations with behavioural problems were estimated using logistic regression models, incorporating multiple imputation for missing data. Path analysis was used to assess four possible mediators (physical activity, air pollution, sleep, and maternal mental health). The qualitative study was conducted with seven focus groups of 34 adolescents aged 15–16 years, purposively sampled by socioeconomic status. Discussions explored use patterns, perceived benefits, and preferences regarding parks. Transcripts were thematically analysed using a hybrid deductive–inductive approach to identify recurrent themes and contextualise quantitative findings. Environmental exposure assessment relied on geographic information system (GIS) tools (ArcGIS, QGIS)

to geocode addresses, compute indexes, and derive buffers around homes and schools. Data analysis was conducted in R, using packages for mixed models, mediation, and imputation.

Results: The study of intelligence showed that having green spaces up to 800 meters of the residence was positively associated with performance IQ [β (95% CI) = 1.30 (0.26; 2.35)] and global IQ [β (95% CI) = 1.27 (0.18; 2.36)], with physical activity appearing to have a minor mediation role. Accessibility to blue spaces had no clear association with any of the outcome measures. The lung function study showed that increasing the NDVI exposure over time within 100 meters of the residence was associated with higher values of FEV₁ [β (95% CI) = 0.01 (0.0002; 0.03)] and FEF_{25-75%} [β (95% CI) = 0.02 (0.001; 0.05)], with no mediation effect detected from either physical activity or pollution. No association was found between blue spaces and the lung function parameters studied. In the study on behaviour problems, results showed that higher exposure to greenness was associated with lower prevalence of reported behavioural problems, in the form of non-tree vegetation, at birth and on average within 100 meter [OR (95% CI) = 0.986 (0.976, 0.996)] and [OR (95% CI) = 0.987 (0.979, 0.996)], and NDVI on average within 100 meter [OR (95% CI) = 0.242 (0.064, 0.907)], and higher exposure to non-vegetated areas at 100 meter buffer was associated with increased reports of behavioural problems at birth and on average [OR (95% CI) = 1.009 (1.003, 1.016)] and [OR (95% CI) = 1.009 (1.003, 1.015)]. From the included mediators only one had statistical significance. Higher greenness was associated with worse maternal mental health which then associated with more reported behavioural problems. Finally, from the focus groups, participants reported regular use of green spaces to perform physical activity, rest, and to socialize. There was a perception of better well-being and respiratory and mental health associated with utilising the parks. According to adolescents, to promote utilisation, parks should be large and multifunctional, with a variety of equipment and sufficient flora. They should be easily accessible from the residence and from school, well maintained, and with programmed activities.

Conclusion: This thesis demonstrates that neighbourhood green spaces play an important role in shaping children's health and development, though effects vary across outcomes and contexts. Accessibility to residential green spaces was positively

associated with children's intelligence. Increases in exposure to greenness across childhood was linked to better lung function. Surrounding greenness was also associated with fewer behavioural problems. And qualitative findings showed that adolescents value green spaces for socialisation, relaxation, and physical activity, while also highlighting unmet needs regarding safety, maintenance, and inclusivity. These findings underscore that green spaces are important determinants of child health. They influence multiple domains through pathways that accumulate across development. Promoting urban greening, together with participatory approaches that incorporate children's and adolescents' perspectives, is essential to promote child health. Such planning should prioritize equity to maximize and ensure broad public health benefits.

Resumo

Introdução: O modelo eco-social de Krieger mostra que a saúde resulta de interações dinâmicas a múltiplos níveis e que estas influências são incorporadas ao longo de toda a vida. Os estudos em saúde urbana mostram ainda que as cidades acumulam simultaneamente oportunidades e riscos, isto é, o acesso a cuidados de saúde e acesso à educação coexistem com exposições à poluição, às ilhas de calor e a fortes desigualdades entre diferentes territórios. Os espaços verdes e azuis desempenham um papel único neste panorama. A investigação mostra que o contacto com estes espaços promove a resiliência, a empatia, a curiosidade e as interações sociais, ao mesmo tempo que atenua riscos ambientais como a poluição ambiental, o ruído e o calor. Melhoram a qualidade do ar, moderam o calor, promovem a atividade física, reduzem o stress e fomentam a coesão social. Estudos cada vez mais têm associado estes espaços a redução da mortalidade, melhor saúde cardiovascular e respiratória, maior bem-estar mental e maior desenvolvimento cognitivo. Nas crianças, estes benefícios são especialmente relevantes, dada a sua sensibilidade durante o desenvolvimento, e a marca duradoura das exposições nos primeiros anos de vida. Apesar da evidência estar a aumentar, ainda existem lacunas importantes. A maioria dos estudos continua a ser transversal, limitando a compreensão de períodos críticos e sensíveis de desenvolvimento e de efeitos cumulativos ao longo da vida. Os espaços azuis também ainda permanecem relativamente pouco explorados, e persistem inconsistências metodológicas na forma como a exposição é definida e medida.

Objetivos: A questão de investigação que orienta esta dissertação de doutoramento é: Os espaços verdes e azuis influenciam a saúde das crianças ao longo do crescimento? Para responder a esta questão, a tese definiu quatro objetivos específicos: (I) examinar a associação entre a exposição a espaços verdes e azuis residenciais e escolares e a inteligência das crianças; (II) investigar a influência da exposição a espaços verdes e azuis na saúde respiratória e nas trajetórias de função pulmonar das crianças; (III) avaliar a relação entre a vegetação circundante e os problemas comportamentais na infância, considerando exposições cumulativas ao longo do crescimento; e (IV) explorar as percepções, experiências e preferências dos adolescentes relativamente aos espaços

verdes, com enfoque nos modos de utilização, benefícios percebidos e características desejadas.

Métodos: Esta tese investiga a forma como os espaços verdes e azuis influenciam a saúde das crianças através de três estudos quantitativos e um estudo qualitativo, todos baseados na coorte de nascimento Geração XXI (G21), no Porto, Portugal. A G21 recrutou 8647 recém-nascidos em 2005–2006 e tem vindo a acompanhá-los em múltiplos momentos, com recolha abrangente de dados de saúde, sociodemográficos e ambientais. Para o estudo sobre inteligência foram analisadas 3827 crianças que realizaram uma avaliação da inteligência aos 10 anos. A exposição foi estimada a partir de índices construídos a partir de imagens de satélite (índice de vegetação por diferença normalizada (NDVI)) e de medidas de acessibilidade a espaços verdes e azuis em torno da residência e da escola. A inteligência foi medida pelo quociente de inteligência (QI) verbal, de execução, e global, através da Escala de Inteligência de Wechsler para Crianças. As associações foram estimadas através de modelos de efeitos mistos ajustados para confundidores sociodemográficos, com ajustes adicionais para avaliar dois possíveis mediadores (atividade física, poluição atmosférica). Para o estudo da função respiratória foram incluídas 3278 crianças com dados de função pulmonar aos 10 anos. A espirometria foi realizada segundo protocolos padronizados, tendo sido avaliada a capacidade vital forçada (FVC), o volume exalado no primeiro segundo (volume expiratório forçado no primeiro segundo (FEV₁) e o fluxo expiratório forçado durante a expiração de 25–75% da capacidade vital forçada (FEF_{25–75%}). A exposição foi estimada a partir de índices de satélite (NDVI) e de medidas de acessibilidade a espaços verdes e azuis em torno da residência. As exposições foram modeladas em vários momentos da infância para captar trajetórias ao longo da vida, e as associações avaliadas com modelos de regressão linear ajustados para confundidores sociodemográficos. Foi ainda realizada análise de mediação para avaliar dois possíveis mediadores (atividade física, poluição atmosférica). Para o estudo acerca dos problemas comportamentais foram incluídas 6269 crianças com avaliações de comportamento aos 7 anos, baseadas em informação relatada pelos cuidadores. A exposição foi avaliada através de medidas geradas a partir de imagens de satélite (NDVI, área com cobertura vegetal que não árvores, área arborizada e área sem cobertura

vegetal). As exposições foram avaliadas em diferentes momentos da infância, e as associações com problemas comportamentais testadas com modelos de regressão logística, recorrendo a imputação múltipla para dados omissos. A análise de mediação considerou quatro potenciais mediadores (atividade física, poluição atmosférica, sono e saúde mental materna). O estudo qualitativo foi realizado com sete grupos focais e envolveu 34 adolescentes de 15–16 anos, selecionados intencionalmente para representar diferentes estatutos socioeconómicos. As discussões exploraram modos de uso, benefícios percebidos e preferências relativamente aos parques. As transcrições foram analisadas tematicamente através de uma abordagem híbrida dedutiva–indutiva para identificar temas recorrentes e contextualizar os resultados quantitativos. A avaliação das exposições ambientais recorreu a ferramentas de sistemas de informação geográficos (GIS) tais como (ArcGIS, QGIS) para georreferenciar endereços, calcular índices de vegetação e gerar buffers em torno das residências e escolas. A análise estatística foi realizada em R, utilizando pacotes para modelos mistos, mediação e imputação.

Resultados: O estudo sobre inteligência mostrou que a presença de espaços verdes num raio até 800 metros da residência se associou de forma positiva ao QI de execução [β (95% CI) = 1.30 (0.26; 2.35)] e ao QI global [β (95% CI) = 1.27 (0.18; 2.36)], sendo a atividade física um mediador marginal do efeito. A acessibilidade a espaços azuis não apresentou associação clara com nenhuma medida. O estudo sobre a função pulmonar mostrou que o aumento da exposição a NDVI ao longo do tempo, num raio de 100 metros da residência está associado a valores mais elevados de FEV₁ [β (95% CI) = 0.01 (0.0002; 0.03)] e FEF_{25-75%} [β (95% CI) = 0.02 (0.001; 0.05)], não se tendo detetado efeito de mediação pela atividade física ou poluição. Não foram encontradas associações entre a exposição a espaços azuis e os parâmetros de função pulmonar estudados. No estudo sobre problemas comportamentais, os resultados mostraram que níveis mais elevados de exposição a vegetação associaram-se a menor prevalência de problemas comportamentais, na tipologia de áreas com cobertura vegetal que não árvores num raio de 100 metros, ao nascimento e em média [OR (95% CI) = 0.986 (0.976, 0.996)] e [OR (95% CI) = 0.987 (0.979, 0.996)] e NDVI em média num raio de 100 metros [OR (95% CI) = 0.242 (0.064, 0.907)], enquanto maior exposição a áreas sem cobertura vegetal num raio

de 100 metros ao nascimento e em média se associou a maior prevalência de problemas comportamentais [OR (95% CI) = 1.009 (1.003, 1.016)] e [OR (95% CI) = 1.009 (1.003, 1.015)]. Dos mediadores estudados apenas um apresentou significância estatística. Mais vegetação associou-se a pior saúde mental materna que por sua vez se associou a maior prevalência de problemas comportamentais. Nos grupos focais, os participantes reportaram utilização regular dos espaços verdes para atividade física, descanso e socialização. Foi percebido maior bem-estar e melhor saúde respiratória e mental na utilização destes espaços. De acordo com os adolescentes, para promover a utilização dos espaços, estes devem ser grandes e multifuncionais, com diversos equipamentos e flora. Devem ser de fácil acesso a partir da residência e da escola, bem mantidos e com atividades programadas.

Conclusão: Esta tese mostra que os espaços verdes desempenham um papel importante na saúde e desenvolvimento das crianças, embora os efeitos variem entre medidas de saúde e contextos. A acessibilidade a espaços verdes residenciais associou-se positivamente à inteligência das crianças. O aumento da exposição a vegetação ao longo da infância associou-se a melhor função pulmonar. A vegetação também se associou a menos problemas comportamentais. Os resultados qualitativos mostraram que os adolescentes valorizam os espaços verdes para interação social, descanso e atividade física, ao mesmo tempo que apontam necessidades não satisfeitas em matéria de segurança, manutenção e inclusão. Estes resultados sublinham que os espaços verdes são determinantes importantes da saúde das crianças. Influenciam múltiplos domínios através de vias que se acumulam ao longo do desenvolvimento. Políticas que promovam arborização, em conjunto com abordagens participativas que incorporem as perspectivas de crianças e adolescentes, são essenciais para promover a saúde das crianças. Este planeamento deve priorizar a equidade para maximizar e garantir os ganhos em saúde pública.

1. INTRODUCTION

1.1. Preamble

1.1.1. Morning Among the Reeds

Late morning light falls on a small pond edged with reeds and wildflowers. The air is rich with the scent of damp earth and sweet vegetation. Water striders dimple the pond's glassy surface, leaving gentle ripples that catch the golden sun. In the shallows, frog eggs cling like beads to the submerged grasses. A dragonfly hovers, its wings flickering blue and green. Everything is calm here. Each rustle of leaf and each croak of a frog is part of a quiet conversation in nature's own language.

A young child kneels at the water's edge, fingers trailing in the cool shallows. A grin of discovery lights up his face as a turtle pokes its head above the water. A blackbird calls from a nearby willow, and the child turns toward the sound, eyes wide with wonder. The world in this moment feels boundless and safe. In this natural sanctuary, time seems to slow. For a brief moment, child and nature are inseparable. There is no rush, no itinerary, only the spontaneous play of a young explorer and the quiet patience of the living earth. Here, at least, lies a corner of the world where the bond between a child and the natural world still thrives, unbroken and alive, in the golden hush of late morning.

But beyond the pond's ring of whispering reeds the spell of morning is fragile. The pond itself is only a small fragment of green and blue in a patchwork of development. Beyond its margins, concrete and steel prevail. Fences mark property lines where fields once ran free, and the chorus of crickets is silenced by the background hum of highways and power lines. Even in places where remnants of the natural world survive, their presence is precarious, boxed in by development, polluted by neglect, or rendered invisible by distraction. This slow erosion is not random, nor is it without consequence.

1.1.2. Childhood Under Glass and Concrete

Scenes of children immersed in mud and sunlight are growing scarce, especially in the Western world. Today, outdoor play is becoming achingly rare for children [1]. More and more of a child's day now unfolds beneath the glow of electronic screens, while the

unhurried joys of unstructured outdoor play quietly fade into the background [2]. What was once a daily reality, like making forts in the woods, chasing butterflies in a vacant lot, or climbing trees, is becoming an occasional outing or a never-known experience.

How did we arrive here? If we're looking for the guilty, we need only look into a mirror¹. Suburban sprawl and city planning have carved childhood into fenced yards and paved streets, leaving few wild havens. A single generation ago, a child might roam freely across a neighbourhood, exploring woods and fields with friends. Now, that roaming territory has shrivelled to a fraction of what it was: one study found that kids have only about one-ninth the free roaming range their parents enjoyed [3]. Busy roads and endless concrete make parents hesitate to let kids wander, and in many communities, the woods where children once played have been replaced by parking lots or fenced-in backyards. Our built environment prioritizes cars and commerce over playgrounds and ponds, quietly telling children that they belong on the sidewalk or indoors, not out "where the wild things are."

Modern culture, driven by consumerism and the churn of capitalism, has also played its part in this great displacement. In an economy that monetizes attention, even the leisure of children has become a commodity to capture. Bright screens have flooded childhood with easy entertainment, each product engineered to keep eyes engaged and thumbs busy. There is always another show to stream, another level to beat, another app begging to be opened. Nature, by contrast, offers no neon lights, no instant validation, nor in-app purchases. Its rewards are subtle, immeasurable, surging in quiet discoveries and gradual wonders. Consumer culture markets an idea of play that comes in a box or on a screen, displacing the unstructured adventures that once forged lifelong memories and dreams. In the process, childhood is increasingly forced to live under (the) glass and with a luminous glow. Contained, curated, commercialized.

Cultural attitudes have also reinforced this shift. Society now often equates roaming in nature with risk and staying inside with safety. In our era of hyper-vigilance, well-meaning caregivers and schools have often chosen structured, supervised activities over free play

¹This is a reference to "V for Vendetta", where the line "If you're looking for the guilty, you need only look into a mirror" confronts the reader with personal and collective complicity. While today's landscape may resemble "Brave New World" dystopia which is marked not by repression, but by distraction, comfort, and passive disengagement, this line remains the most powerful indictment of collective responsibility I could find.

under the sun. As a result, countless children are kept on tight leashes, their days packed with lessons, activities, screens and supervision. Their lives measured, sanitized, contained. The unhurried freedom of a childhood spent exploring fields and creeks becoming tales of legend. The hum of insects and the whisper of pines have been drowned out by the buzz of electronics and constant adult oversight. Or just surviving as echoes in videos and reels.

1.1.3. What Children Lose

What does the natural world offer children? In the green recesses of a forest, or the muddy edge of a pond, children find more than just play. They find resilience, empathy, and curiosity taking root. Climbing a tree and scraping a knee teaches resilience, the quiet lesson that one can fall, get up, and try again. Watching over a ladybug or discovering a bird's nest nurtures a budding empathy, as they learn to respect and care for lives other than their own. Following a trail of ants or marvelling at the stars sparks curiosity, inviting questions and a sense of awe at how vast and interconnected life can be. In wild places, the young intuitively absorb nature's rhythms. Such experiences sow seeds of confidence, compassion, and creativity that can last a lifetime.

Yet, these are the very qualities that are at risk in a childhood spent largely divorced from nature. A generation growing up behind walls and screens can miss out on learning how to weather life's small storms. When every skinned knee is avoided, and every rain shower means staying inside, resilience can atrophy. When animals are seen only on glowing screens or not at all, it is harder for a child to understand, to feel reverence or compassion for the living things they've never met. Opportunities to develop empathy fade when playmates are virtual and pets or wild critters are absent. Curiosity, too, can wither in a climate of digital saturation and rigid schedules. Answers to trivial questions are always a click away, and deeper thinking quietly fades into oblivion.

Today's typical child navigates a landscape of apps and organized activities, leaving little room for the serendipity of unstructured exploration. Social isolation has also grown. Gone are the roving packs of neighbourhood kids inventing games until dusk. Instead,

they are interacting through avatars and text messages, with a sense of loneliness despite being constantly “connected”.

1.1.4. Restoring Nature to the Heart of Childhood

But the story does not have to end here. If the bond between children and nature has been frayed by design and neglect, it can also be mended through intention, imagination, and systemic change. The trends that have siloed children away from green and blue spaces are not inevitabilities. They are human choices. They can be unchosen. Around the world, a quiet movement is gathering momentum: to bring nature back into the heart of childhood, and to recognize it not as peripheral enrichment, but as essential infrastructure for human flourishing.

This movement echoes the central warning of the “Last Child in the Woods”, where Richard Louv describes “nature-deficit disorder” [4]. Louv calls out the costs of severing childhood from the natural world: diminished use of the senses, attention difficulties, higher rates of physical and emotional distress. These are not abstract outcomes; they manifest in classrooms and clinics, in the rising tide of anxiety and disconnection in the very generation most saturated with digital connectivity. And yet, as Louv argues, this deficit is a crisis, but it can also be an opportunity. An opportunity to rebuild the pathways, both literal and symbolic, that once led children out the door and into the wild.

We cannot afford to raise “the last child in the woods.” To do so would be to sever not only individual well-being, but our collective ecological heritage. Each child we raise without nature is one more adult potentially estranged from the living systems that sustain us all. And each policy, design choice, or social norm that keeps children indoors is a quiet vote against the future of planetary health.

And yet, the good news is that reconnection is not only possible, but already blooming. School gardens flourish in city centres. Forest kindergarten programs are taking root even in dense urban areas. Paediatricians prescribe time outdoors. Local governments are investing in greenways and blue corridors not just for aesthetics, but also for equity and health. There is a widening recognition that access to nature is a public good, and childhood without it is incomplete. Nature is not a luxury reserved for the few. It is a

birthright that every child deserves. This thesis tries to bring support to that world. A world in which the question is not whether nature belongs in childhood, but how we ever believed it could be left out.

1.2. Eco-Social Model

1.2.1. Socio-Ecological Precursors

Understanding the relation between health and green and blue spaces requires theoretical models that connect the individual with broader systems. Nature is not experienced in isolation but within layered contexts, like family, school, neighbourhood, city, and society. As such, socio-ecological models are foundational for research linking environmental exposures to health [5]. These frameworks illustrate how access to nature operates at multiple scales, both spatially as well as temporally. They also provide the conceptual grounding for later theories like Nancy Krieger's eco-social model [6].

A seminal contribution to socio-ecological thinking came from Urie Bronfenbrenner's ecological systems theory, developed in the 1970s and formalized in the 1980s [7]. His model used nested circles to illustrate the multiple environments surrounding the individual: the microsystem of family and school; the mesosystem of their interactions; the exosystem of community settings with indirect effects; the macrosystem of societal and cultural values; and the chronosystem, embedding these relationships in historical time [8, 9].

This multilevel ecological framing laid important conceptual groundwork for public health. Dahlgren and Whitehead's "rainbow model" mapped the main determinants of health into concentric layers: individual lifestyle factors at the core, surrounded by social and community networks, living and working conditions, and broader socioeconomic, cultural, and environmental conditions. The model highlights layered determinants from individual to broader socioeconomic and environmental conditions [10].

Building on this, Barton and Grant's health map expanded the rainbow into a more explicit integration of urban planning, sustainability, and ecosystem perspectives. Their model situates health in relation to human settlements, natural systems, and the global environment, highlighting the interdependence of social, economic, and ecological factors [11]. Together, these socio-ecological models established that health is co-produced by layered, multi-scalar influences.

1.2.2. The Eco-Social Model

The eco-social model is a framework in epidemiology that seeks to explain how social and environmental conditions jointly influence health and disease in populations. First articulated by Nancy Krieger [6], it emerged as a response to earlier epidemiologic paradigms that were deemed too narrow or fragmentary. It proposed to integrate multiple hierarchical levels of causation within a single framework, emphasizing that population health is deeply embedded in the environmental and social context [12]. The model has since evolved to encompass contemporary issues like globalization, climate change, and environmental injustice [13], but its central premise remains the same: health and disease cannot be separated from the environmental context and social structure in which people are immersed. Today, the eco-social model is considered a foundational theory in epidemiology for studying how “people literally embody, biologically, their lived experience” within specific social and environmental contexts [14].

1.2.3. Core Constructs of the Eco-Social Theory

At the heart of the eco-social model are several constructs that explain how social and environmental conditions become biologically embodied.

The first construct, embodiment, refers to the incorporation of the physical and social world around people. Individuals are not passive recipients of exposures but active sites where influences are inhaled, ingested, absorbed, and ultimately reflected in cells, organs, and systems. Over time, repeated exposures leave biological imprints that are reciprocal and cumulative, as biology also shapes behaviour that can modify exposures. This idea has particular salience for children’s health, since childhood represents a critical window of sensitivity to environmental and social conditions. A compelling illustration comes from a longitudinal twin cohort in Belgium: urban children with more residential green space had higher IQ scores and fewer behavioural problems compared to peers with less green access [15]. Methodologically, embodiment underscores the value of life-course epidemiology and longitudinal cohort studies, which make it possible to observe how exposures during sensitive periods are carried forward, shaping later outcomes [14].

Closely related are the pathways of embodiment, which delineate the routes through which social and environmental factors influence health. These pathways may involve direct physical exposure, like toxins or pathogens, but also social exposures, such as poverty, and discrimination. They can operate quickly, as in an acute infection, or slowly, as in the long-term effects of chronic stress, and may even extend across generations, such as when maternal malnutrition shapes offspring health. For instance, a Barcelona cohort study found that greener school environments improve working memory and reduce inattentiveness in children, likely through mechanisms such as fresh air, reduced pollution, and restorative effects [16]. Studying such complex pathways requires approaches that can combine quantitative assessment of exposures with qualitative insights into lived experience. Mixed-methods research, ethnography, and contextual qualitative interviews are therefore natural complements to epidemiologic measurement, helping to explain how individuals perceive and respond to the environments in which they live [14].

Another construct is the cumulative interplay of exposure, susceptibility, and resistance. Health is shaped not by single exposures but by their accumulation across the life course and their interaction with individual and group-level susceptibilities. Exposures can compound or mitigate one another, and their impact depends on timing and duration. For example, research in Denmark has shown that children who grew up with the lowest levels of greenness had markedly higher risks of psychiatric disorders in adulthood than their peers in greener areas, even after accounting for socioeconomic status (SES) and family history. Cumulative childhood exposure mattered more than single-year measures [17]. Methodologically, this points toward multilevel models, which allow researchers to account for nested structures (individuals within families, neighbourhoods, or regions), and for systems science methods which can capture the feedback and synergy of exposures over time [18].

Finally, the construct of agency and accountability highlights that health patterns are not inevitable outcomes of biology or chance, but consequences of decisions and structures. Agency refers to the capacity of individuals, communities, and institutions to act in ways that influence health, while accountability directs attention to the actors responsible for producing or perpetuating inequities. For example, involving youth in

green space planning can empower communities and create more equitable and health-promoting environments. A study examining children's participation in green space planning linked these efforts directly to enhanced environmental justice and youth agency [19]. This requires methods that extend to policy analysis, participatory research, and evaluation of interventions, ensuring that accountability is built into both the production and use of knowledge [14].

1.3. Urban Health

1.3.1. Defining Urban Health

Urban health studies the social and physical characteristics of cities that influence health [20]. Urban environments shape exposures and outcomes by mediating contact with protective or harmful factors. Cities concentrate economic opportunity and services, which can improve health care access and educational outcomes for children [21]. At the same time, cities also concentrate hazards: high population density and heavy traffic contribute to air and noise pollution, dense built environments can create urban heat islands, and socioeconomic inequalities tend to be starkly visible across different neighbourhoods [22]. The urban topography influences daily exposures such as the quality of the air, the ease of walking or cycling, and the availability of green space for recreation. Socially, urban living can affect cohesion and stress: anonymity or heterogeneity in large cities may weaken social networks for some, while diverse communities can also foster vibrant social support in others. Urban environments also shape health behaviours (diet, physical activity) through the food landscape and the built environment's design (availability of parks, playgrounds, sidewalks) [23].

A central concern in urban health is inequity. Unlike rural settings where disparities may be more geographically distributed, urban inequities can manifest over small areas, sometimes varying from street to street [24]. Affluent urban districts may enjoy clean streets, greenery, and abundant services, while marginalized neighbourhoods experience overcrowded housing, degraded environments, and limited services [24]. The World Health Organization (WHO) emphasizes that unplanned urbanization often has negative health impacts that hit the poorest hardest, reinforcing the need for deliberate healthy urban planning [24].

1.3.2. Global Urbanization: Trends and Patterns

Urbanization is a defining global trend of the 21st century. As of 2025, the urban share of the global population is estimated at around 58%, up from 56% in 2020 and projected to reach 70% by mid-century [25, 26]. This includes a significant demographic shift for

children. In 2020 there were an estimated 1.18 billion children residing in urban areas globally [27]. By the 2050s, nearly 60% of all children are projected to live in urban settings, reflecting the fact that urban population growth will concentrate in regions with youthful populations (Africa, Asia, and Latin America) [26].

Cities are also growing larger. The number of megacities (defined as urban agglomerations with over 10 million inhabitants) has expanded. In 1990, there were 10 megacities, in 2018 there were 33, and by 2030 the world could have 43 megacities [26]. Megacities concentrate both extreme population density and complex governance challenges, with severe internal inequalities. Large cities with 1 to 5 million residents and peri-urban areas are also growing rapidly. Peri-urban sprawl (the expansion of cities into fringe areas) is a notable pattern, especially in Africa and South Asia, where urban population growth often outpaces formal planning. This can lead to large informal settlements or slums on city edges. Globally, it is estimated that around 1 billion people live in slums [28]. The number of children in slums is estimated at 350 to 500 million and could triple by 2050 if current trends continue [29].

The trends of urbanization are not uniform. In high-income countries, urbanization is plateauing at high levels, while much of the rapid urban growth is occurring in low- and middle-income nations [26]. That means the burden of providing healthy urban environments for children is particularly acute in developing regions, where resources may be limited and governance structures strained. Many of these cities already struggle with inadequate housing, water, and sanitation systems, raising concerns about the “urban advantage” in health. Children in urban areas have averaged better health outcomes than rural children (greater access to immunization, healthcare, and schooling contributes to lower mortality and better growth on average) [30]. But the urban advantage can mask inequities. United Nations International Children's Emergency Fund (UNICEF) has described this as an “urban paradox”: cities offering both opportunity and inequality, meaning some urban children thrive while others suffer conditions as dire as those in the poorest rural areas [28].

Rapid and unplanned urbanization has introduced or exacerbated a triad of health challenges in cities worldwide. The WHO highlights a “triple threat” in urban areas: the

rising burden of non-communicable diseases, persistent infectious disease risks, and increased risk of injuries and violence [24].

1.3.3. Europe and Portugal in the Global Context

These global patterns have specific expressions in Europe and Portugal. Europe is already highly urbanized, with 74% of its population living in urban areas in 2018, a value projected to rise to 85% by 2050 [26]. European urbanization differs from that in Africa or Asia, being dominated not by megacities but by a dense network of medium-sized cities and metropolitan regions. Only a handful of European cities, such as Moscow and Paris, are megacities, while most urban residents live in smaller metropolitan areas. Key challenges include urban sprawl, peri-urbanization, aging infrastructure, climate vulnerability, and persistent inequalities in housing and environmental exposures [31].

In Portugal, approximately 74.7% of the population lived in urban areas in 2023, according to INE official estimates [32]. Lisbon and Porto metropolitan areas are home to about 2.9 million and 1.7 million people respectively [32], and concentrate much of the country's urban dynamics and associated health challenges [33]. Both cities face growing concerns related to air pollution, noise, traffic injuries, and urban heat islands. For instance, a recent analysis of Porto shows that lack of green infrastructure exacerbates heat stress and air pollution, particularly in socioeconomically disadvantaged neighbourhoods [34].

For children, Portugal also demonstrates the “urban paradox” [28]. On average, urban children benefit from strong healthcare and education systems, reflected in high immunization coverage and low child mortality. Research in Porto identified “hotspots” of childhood obesity in deprived neighbourhoods, underscoring uneven health outcomes even within the same city [35]. Thus, while urban Portugal embodies many of the advantages of European welfare states, it also reflects the spatial and social disparities that characterize contemporary urban health.

1.3.4. Key Environmental Health Determinants in Urban Settings

Urban settings bring together a matrix of environmental, infrastructural, and social conditions that shape population health. Three overlapping domains are used: the physical–built environment, the social environment, and service/access infrastructures [36]. In this case the physical–built environment consists of the material features and exposures arising from the urban fabric and its geographies like air quality, heat, noise, housing conditions, street networks, land use, and the presence of green and blue spaces [37]. The social environment encompasses patterns of socioeconomic stratification, social cohesion, safety, and collective efficacy that influence stress, behaviour, and opportunity [38]. Service/access infrastructures concern the distribution and reachability of health care, education, healthy food, and recreational amenities [39, 40]. These categories are analytically useful but not independent. They intersect. For example, traffic-oriented planning affects air pollution and noise, which in turn can concentrate in deprived neighbourhoods and interact with access to parks and primary care.

Within the physical–built environment, urban air quality remains a central determinant of child health. Combustion from transport, industry, and heating elevates particulate matter and traffic-related gases such as nitrogen dioxide and ozone, and a substantial share of urban residents experience levels that exceed guideline values [41]. Children are uniquely susceptible because their lungs are developing, their minute ventilation per body weight is higher, and their time–activity patterns often bring them closer to street-level emissions. Exposure to particulate matter with a diameter of 2.5µm or less (PM_{2.5}) and nitrogen dioxide (NO₂) is associated with higher incidence and exacerbation of asthma [42, 43], reduced lung-function growth [44], and potential neurodevelopmental effects [45].

Heat is another important urban exposure. Materials that absorb and re-radiate heat, coupled with limited evapotranspiration, produce urban heat islands whose differentials intensify during heatwaves [46]. Infants and young children, with immature thermoregulation and limited autonomy, face heightened risks of dehydration, heat exhaustion, and heat stroke [47]. Heat also affects cognitive performance and schooling, with studies noting more absences and lower attainment during extreme heat days [48].

Importantly, heat burdens are socially patterned. Neighbourhoods with sparse tree cover and inadequate housing quality experience higher indoor and outdoor temperatures, while wealthier districts often benefit from greener microclimates and access to cooling, deepening inequities [49].

Chronic environmental noise, largely from transport and industrial sources, is similarly pervasive. Sustained exposures above commonly used harm thresholds are widespread in cities and have been associated in children with impaired reading development, attentional difficulties, altered stress physiology, and symptoms consistent with anxiety or hyperactivity [50]. Noise concentrates along major corridors and in lower-SES areas, often co-occurring with air pollution and traffic danger. The cumulative effect of these exposures is greater than the sum of their parts, reinforcing disadvantage where resilience resources are thinnest [51].

Housing conditions are a critical mediator between external urban exposures and children's health. Substandard structures, damp and mold, inadequate ventilation, and poor thermal comfort contribute to respiratory symptoms, infectious disease transmission, injuries, sleep disruption, and stress [52]. Overcrowding facilitates respiratory and gastrointestinal infections, reduces quiet space for study and sleep, and is associated with poorer developmental outcomes [53].

Street design, land-use patterns, and mobility systems link directly to children's daily behaviour. Neighbourhoods with connected street grids, sidewalks, safe crossings, traffic calming, and accessible destinations support independent mobility and routine moderate-to-vigorous physical activity, with downstream benefits for healthy weight trajectories [36]. Robust public transport extends these gains by promoting incidental walking and reducing car dependence, indirectly improving air quality and injury risk profiles. Conversely, environments hostile to pedestrians like lacking sidewalks, adequate lighting, or safe crossings constrain outdoor play and reinforce sedentary indoor time [54].

Green and blue spaces are a distinctive component of the physical-built domain because they simultaneously modulate multiple exposures. Vegetation cools microclimates, buffers noise, and enhances the perceived restoration effect of local

environments. Child-friendly natural spaces encourage play, social interaction, and potentially support immune development through biodiverse contact [5]. Proximity to green and blue spaces is generally associated with better mental well-being and more physical activity among children, although benefits depend on safety, maintenance, accessibility, and age-appropriate design [55]. However, access to nature is not evenly distributed: greener neighbourhoods typically align with higher SES, which places equitable greening on the agenda as both a health and environmental justice priority [56].

The social environment shapes how these physical–built exposures are experienced and with what consequences. Socioeconomic segregation concentrates hazards and thins protective resources in predictable geographies. Using the Portuguese version of the European Deprivation Index (EDI), it was shown a graded, dose-response relation between area deprivation and all-cause mortality. Compared with the least deprived areas, mortality risk rose progressively [57]. Building on that index, it was found persistent life-expectancy gaps: at birth, the most deprived had shorter life-expectancy than the least deprived. These differentials attenuated with age and were smallest at older ages, but they did not disappear at the population level [58]. A multicohort analysis showed clear effect modification by SES. The mortality penalty of living in disadvantaged neighbourhoods was markedly stronger among people with low education, underscoring that neighbourhood context and individual resources interact to widen inequalities [59]. Work on biological embedding provides a plausible pathway: across cohorts in Switzerland, Portugal and the UK, higher neighbourhood deprivation was associated with elevated allostatic load, a multisystem “wear-and-tear” marker that links place, stress physiology and downstream disease risk [60].

Service and access infrastructures mediate whether urban proximity translates into realized opportunity. Living in a city does not guarantee equitable access to paediatric primary care, preventive services such as vaccination, or school-based supports. Where services are distant, overburdened, or culturally misaligned, children experience delays in care and lower uptake of preventive interventions [61]. Quality early childhood education and stable childcare settings underpin cognitive and socioemotional development and help establish healthy routines. The local food environment also matters: in some low-income areas, high densities of fast-food outlets and limited

availability of fresh produce contribute to energy-dense, nutrient-poor diets and the “double burden” in which food insecurity coexists with obesity risk; conversely, supermarkets, farmers’ markets, and strong school meal programs can improve diet quality [62]. Access to safe recreational facilities and community centres increases routine physical activity and positive social engagement, while reliable public transport and digital connectivity expand the effective reach of health, education, and recreational services. Poor connectivity isolates families and inflates the time and financial costs of care-seeking and school engagement, widening disparities [61].

1.4. Defining Green and Blue Spaces

1.4.1. Conceptual Definitions

Green and blue spaces can have multiple definitions. Broadly, green space refers to vegetated areas, while blue space refers to places where water is the defining feature. The WHO often adopts the definition of urban green space (UGS) as “all urban land covered by vegetation of any kind,” encompassing street trees, gardens, lawns, and parks [63]. Blue spaces are analogously treated as visible, outdoor waterbodies (natural or man-made) such as coasts, rivers, lakes, ponds, canals, and fountains [64, 65]. Blue spaces have also been conceptualized more explicitly as “health-enabling places and spaces, where water is at the centre of environments with identifiable potential for the promotion of human wellbeing,” emphasizing their therapeutic qualities [66].

There is no single, universally accepted definition of green or blue space, and usage differs across fields and study designs. WHO’s evidence reviews state plainly that definitions of UGS vary, sometimes including street trees and even certain water elements. The choice of definition often reflects the study’s health pathways and data constraints [67]. Taylor and Hochuli’s review shows that “greenspace” is used in at least two broad ways: either as a synonym for “nature” or as explicitly urban vegetation, and it concludes that researchers should make their operational definitions explicit to avoid confusion [68]. Measures capture different constructs: “greenness” reflects vegetation regardless of access or use, whereas “green space” typically denotes mapped, often accessible parks or open areas. Studies comparing vegetation indexes with cartographic datasets demonstrate that exposure estimates can diverge substantially depending on the metric chosen [69, 70].

A second conceptual axis concerns the degree of human intervention, ranging along a continuum from natural to highly engineered environments. At one end are relatively natural ecosystems (unmodified river reaches, remnant woodlands), in the middle are semi-natural, managed settings common in cities (urban parks, restored wetlands, riparian greenways), and at the man-made end are purpose-built infrastructures such as green roofs, living walls, rain gardens, and bioswales that deliver hydrologic and

microclimatic services alongside amenity [71]. These categories blur in practice: urban “nature” spans a continuum from relatively wild to deliberately designed spaces, and in public health research it is not consistently defined by excluding artificial features. Much work treats “nature” and “natural environment” interchangeably while still allowing human-made elements (e.g., designed plantings, constructed waterways) within the exposure, which helps explain why operational definitions vary across studies. Accordingly, authors should state exactly what counts as green or blue space in their analyses (for example, only public natural parks versus any vegetated land or visible surface waters) [72].

1.4.2. Typologies & Examples

In applied public health and urban-environment research, “green space” typically spans the everyday vegetated places of a city: formal parks and gardens (including pocket parks, squares, playgrounds and botanical gardens), linear plantings such as street trees and verge vegetation, larger urban woodlands/forests, community gardens and allotments, private yards and lawns, and other vegetated open spaces such as schoolyards, cemeteries, and vegetated roofs; some studies also treat peri-urban agricultural land within the urban boundary as part of the urban green fabric. This breadth is explicit in cross-disciplinary reviews and typologies, and is consistent with urban-forestry framings that encompass vegetation on both public and private land and across scales, from individual yard trees to wooded fragments and parks [68, 73].

By analogy, “blue space” denotes outdoor environments where water is the defining feature. In cities this commonly includes rivers and streams (often forming linear blue–green corridors), lakes and ponds (natural or constructed, including retention ponds), wetlands and marshes, coastal margins where applicable (beaches, estuaries, lagoons), and also engineered or designed water features such as canals, harbours and waterfronts, fountains, splash pads, and reflective pools. Contemporary public health reviews and the BlueHealth project explicitly treat blue spaces as natural or man-made settings in which water is prominent and accessible, and a number of studies operationalise this to include canals and fountains in exposure measures [64, 74].

Finally, many planning and health papers describe a city's green infrastructure as an interconnected network of natural and semi-natural areas (including water bodies) that collectively provide environmental and health benefits [75].

1.4.3. Measurement & Indicators

Quantifying exposure to green and blue space means translating concepts into reproducible variables. Different measures capture different facets of availability, accessibility, quality, and contact. Studies therefore should justify the indicators in light of the hypothesized health pathways, and be explicit about the neighbourhood and buffer definition used for aggregation. Reviews recommend aligning the metric with the pathway of interest, and triangulating multiple indicators where possible [5].

Satellite vegetation and water indices are widely used because they are globally consistent, free to access, and span long time series (Landsat since 1972; Sentinel missions since 2015). The Normalized Difference Vegetation Index (NDVI), based on red and near-infrared reflectance, remains the most common greenness proxy in epidemiology. It reflects photosynthetically active vegetation on a continuous -1 to +1 scale. Seminal work established NDVI in the 1970s and 1980s [76]. Like any proxy, NDVI has limitations: it saturates in dense canopies (reduced sensitivity at high leaf area) and does not distinguish vegetation structure or type (e.g., tree canopy vs. lawns) without additional data or indices. Alternatives and derivatives can partially reduce saturation. Other frequent indices include Normalized Difference Water Index to delineate open water and urban blue features, and biophysical products such as the Leaf Area Index (LAI) which measures the one-sided leaf area per unit ground area, and reflects canopy density and energy balance. Two structural measures are often reported. Tree (urban) canopy cover is the percentage of ground covered by the vertical projection of tree crowns. It is linked to micro-climate cooling, shade and aesthetic/biophilic effects. LAI captures foliage quantity but, like NDVI, still benefits from pairing with structural data when pathways depend on shade or cooling. Both relate to ecosystem-service pathways (cooling, air filtration). The popularity of these indices stems from: being (i) free/open, (ii)

global, (iii) long-running (comparable archives since the 1970s), and (iv) standardized, so studies in different places and years can be compared more directly [77].

With vector land-use/land-cover layers and vector features (park polygons, rivers/shorelines, street-tree layers), it is possible to derive: proximity (distance to nearest park/river/coast), availability (e.g., percentage area or m² per capita in green/blue classes; percentage tree canopy), counts/area within a neighbourhood (number of parks; total park area), and configuration/fragmentation (patch density, largest patch index, cohesion/connectivity, shape metrics). The same neighbourhood can be used to summarize either raster indices or vector features, so it is valid to compute NDVI, counts, or percentage canopy inside a network service-area buffer or any other neighbourhood definition.

Exposure is highly sensitive to how the neighbourhood/buffer is defined. Two common approaches are Euclidean (circular) buffers and network/isochrone buffers (all streets reachable in 10–15 minutes on foot). Network buffers often better reflect accessibility because physical barriers and street layouts matter for real-world movement. Studies show that circular vs. network buffers can yield meaningfully different exposure estimates and access classifications [78]. Choices should reflect both the pathway and the population. WHO recommends access to at least 0.5–1 ha of public green within 300 m linear distance as a general planning benchmark [67]. For children, shorter home- and school-centred buffers are often justified because independent mobility is limited and most daily time is spent very near home/school. For example, a study in Barcelona used buffers from 50 to 500 meters and showed impacts of surrounding greenness on cognition [16]. In practice, a transparent methods section should: specify the buffer, justify the scale with respect to the hypothesized pathway, and use the relevant neighbourhoods for the participants. Sensitivity analyses across multiple scales are advisable.

Quantity and availability do not guarantee use. Quality features like safety, maintenance, amenities, biodiversity, and shade, modulate whether spaces are appealing and health-promoting. Quality is commonly audited with structured tools. In Porto, for example, neighbourhood accessibility was mapped and all public green spaces were field-audited

using the Public Open Space Tool (POST), revealing socioeconomic inequalities in both access and quality (e.g., more safety issues, fewer amenities in more-deprived areas) [56]. Building on this, a smartphone app was developed to systematize quality assessment in parks and green spaces [79]. Beyond cleanliness, lighting and equipment, biodiversity and vegetation structure matter. Evidence suggests that higher species richness and abundant birdlife can be associated with greater psychological restoration and well-being, although perceived biodiversity may sometimes track well-being more strongly than measured richness, highlighting the importance of both ecological and experiential qualities [80]. The same is true for the species richness and lung function in children [81].

1.5. Influence of Green and Blue Spaces on Population Health

1.5.1. Conceptual Pathways Linking Green and Blue Spaces and Health

A growing body of theory describes how green and blue spaces can influence health through multiple pathways. Three frameworks are often mentioned: ecosystem services, biophilia, and salutogenesis.

Ecosystem services refer to the benefits that natural environments provide to humans, such as air and water purification, climate regulation, and recreation and social interaction [82]. UGS can mitigate environmental hazards by filtering air pollutants, dampening noise, and reducing urban heat islands, thereby buffering communities from extreme weather and heat waves [72, 83]. Green infrastructure also supports cultural ecosystem services: it encourages physical activity, facilitates social cohesion, and provides aesthetic and psychological benefits that enhance well-being [83]. In short, healthy ecosystems underpin healthy populations, aligning with an eco-social view of urban health [72].

The biophilia hypothesis, articulated by Wilson, proposes that people have an evolutionary predisposition to find relief and restoration in natural settings [84]. Contact with nature can evoke positive affect and reduce stress as a psychophysiological response. Two influential theories are often discussed alongside biophilia. Ulrich's stress-reduction theory, proposes that brief exposure to non-threatening natural settings can evoke an evolutionarily shaped, rapid affective response that down-regulates psychophysiological stress [85], and Kaplans' attention restoration theory, which posits that environments high in "soft fascination" and a sense of "being away" engage effortless attention, allowing fatigued directed-attention mechanisms to recover [86]. These theories are compatible with biophilia and help explain how contact with nature may support restoration and mental well-being. These effects operate largely at the individual level, improving mental states and promoting healthy behaviours. Over time, repeated micro-restorative experiences can yield cumulative public health benefits, such as lower prevalence of depression and anxiety in populations with abundant greenness [72]. Biophilia-driven design principles are now employed in architecture and

urban planning to intentionally incorporate natural elements that nurture this human–nature connection [87].

Salutogenesis focuses on factors that support human health and well-being, rather than on risk factors for disease. In the context of green/blue spaces, a salutogenic environment is one that continuously provides cues and opportunities for maintaining physical, mental, and social health [88]. Nature-based settings can be considered salutogenic because they help people restore psychological balance, engage in physical activity, and build social capital. A community garden or urban forest not only reduces harm (by improving air quality or cooling temperatures) but also actively promotes health by offering communal spaces for exercise, play, and stress relief [72]. Urban planners have begun to embrace salutogenic design, aligning city landscapes to promote a “sense of coherence” and well-being [88]. By bringing nature into cities and evoking biophilia, salutogenic design frames landscape interventions as a form of public health promotion. In this way, nature becomes a health asset at individual, community, and societal scales: individuals benefit from stress reduction and exercise, communities benefit from social interaction and safer neighbourhoods, and society benefits from ecosystem resilience and climate adaptation.

1.5.2. Epidemiological Evidence of Health Benefits

All-cause mortality has been linked to green spaces in several studies and meta-analyses. A 2016 systematic review [89] found consistent evidence that residential green space is associated with reduced premature mortality. People living in the greenest neighbourhoods tended to have lower all-cause mortality rates than those in the least green areas, even after adjusting for SES. A meta-analysis of cohort studies [90] quantified this relationship, showing that increased greenness led to lower rates of all-cause mortality. These findings suggest that greener environments confer a survival advantage, potentially through a combination of pathways like improved air quality, enhanced physical activity, and stress reduction. Notably, a recent umbrella review confirmed that green space exposure is associated with reduced all-cause mortality and specifically lower cardiovascular mortality across populations [91]. Evidence on other

causes of death is still less clear, with some studies showing protective associations and others finding no effect.

Cardiovascular health appears especially responsive to green space exposure. Several epidemiological studies have documented lower rates of hypertension, coronary heart disease, and stroke among residents of greener urban areas. Two recent meta-analyses bolster this evidence: Liu et al. found that higher greenness was associated with a significant reduction in cardiovascular disease prevalence and mortality [92], and Bianconi et al. similarly reported that urban green interventions had measurable benefits for cardiovascular and cerebrovascular outcomes [93]. One nationwide cohort from Taiwan found that individuals living amidst more green cover had a lower incidence of type 2 diabetes over time [94], hinting that chronic cardiometabolic conditions may be mitigated by exposure to natural environments. Recent evidence also suggests blue spaces (e.g. coasts, lakes) benefit cardiovascular health, potentially via stress reduction and encouragement of recreational activity; however, this area is less studied than green space [91].

Respiratory health in relation to green space has yielded mixed results, reflecting a balance of positive and negative influences. On one hand, urban vegetation can improve air quality by removing pollutants and particulate matter, leading to lower asthma exacerbation rates and better lung function. Green infrastructure (like tree-lined streets) also mitigates traffic emissions and provides cooler microclimates, which can reduce ozone formation on hot days. On the other hand, certain green environments can exacerbate allergies or respiratory issues through higher pollen counts and mold spores. Overall, the net effect of green space seems to be protective for respiratory health. A 2023 meta-analysis [95] found that higher residential greenness was associated with reduced risk of chronic respiratory diseases, though the effect sizes were modest. The authors note heterogeneity in results, partly because quality of green space matters: well-maintained vegetation that doesn't generate excessive allergens (and that encourages exercise) is ideal. Blue spaces may also aid respiratory health by enhancing air circulation and humidity (e.g., living near the coast has been linked to better asthma outcomes in some studies), but more research is needed.

Mental health is one of the most studied domains. Contact with nature has been linked to lower levels of stress, depression, and anxiety in diverse populations. Green and blue spaces provide settings for relaxation and recovery from daily stressors. Epidemiological surveys consistently show lower prevalence of depression and anxiety disorders among those with abundant neighbourhood nature. Wang et al. [96] reported that long-term residential greenness exposure was associated with a decreased risk of depression and anxiety disorders, using nationwide data in China. In older adults in Porto, living near UGS was associated with lower odds of depression [97]. An umbrella review [98] concluded that green space exposure correlates with better mental health across the life course. These benefits extend to serious mental illnesses: a Danish study found that children who grew up with the lowest levels of green space had up to 55% higher risk of developing psychiatric disorders (like schizophrenia, substance abuse, and mood disorders) in adolescence and adulthood compared to those surrounded by the most greenery [17]. Mechanistically, green settings may reduce rumination and mental fatigue while promoting positive emotions, effects akin to those seen in clinical ecotherapy or “forest bathing” interventions, which reliably show reductions in cortisol and self-reported stress after exposure to forests or parks. Blue spaces (e.g., ocean coasts, riversides) similarly confer mental health benefits. A systematic review of blue space exposure noted consistent associations with improved mood and reduced stress, often with slightly smaller effects than green space but still significant [99]. There is also evidence that views of water (like living near a coastline) correlate with lower psychological distress scores, independent of green vegetation, highlighting water bodies as a restorative environmental feature [100].

Nature contact may also enhance cognitive function. Studies in adults suggest that green space in the living environment is associated with slower cognitive decline in older age and lower risk of dementia, possibly by supporting physical exercise and cardiovascular health [101]. In younger people, short-term memory and attention can improve after interacting with natural environments (the “attention restoration” effect) [102]. In adult working populations, greener commutes have been linked to lower perceived stress [103]. For instance, adults exposed to higher levels of pollution at their residential address had lower scores in a cognitive assessment, implying that poor environmental

quality impairs cognition [104]. While more longitudinal research is needed, current evidence indicates nature exposure supports cognitive health across ages by reducing toxic environmental exposures and by directly restoring mental capacities.

Obesity and sedentarism constitute another domain on which green and blue spaces affect health. Parks, trails, and waterfronts provide inviting venues for exercise, play, and active transport. Numerous cross-sectional studies show that people with greater access to parks or greenways are more likely to meet physical activity guidelines and have lower body mass index (BMI) than those in less green neighbourhoods [105]. A twin study by Cohen-Cline et al. [106] demonstrated that access to green space was associated with higher physical activity levels and better mental health, even after controlling for genetics and family factors. In children, proximity to playgrounds and parks predicts more frequent outdoor play and lower risk of obesity. A systematic review on built environment and paediatric obesity concluded that neighbourhood green space is inversely related to childhood overweight, likely by facilitating active play and safe walking/biking opportunities [107]. Blue spaces similarly promote physical activity and often have a calming effect that can increase exercise adherence. A 2017 review found that individuals living near the coast in England had higher odds of meeting physical activity recommendations and lower obesity prevalence than those inland, suggesting a combined benefit of blue space environments on active lifestyles and weight status [108]. However, when parks are perceived as unsafe or poorly maintained, adults are less likely to use them, so physical-activity outcomes depend not only on the availability of green/blue spaces but also on their quality (e.g., lighting, amenities, upkeep) and on the presence of programming such as supervised activities or organized green-exercise groups [109].

Green infrastructure also contributes to reduced morbidity from extreme heat and improved air quality. Vegetation provides shade and evapotranspirative cooling, which can lower urban temperatures. For example, measurements in Seoul showed that the corridor along the restored Cheonggyecheon stream was 3.3°C to 5.9°C cooler than a parallel street without greenery, mitigating urban heat island effects [110]. Studies have found fewer heat-related hospital admissions and deaths in neighbourhoods with higher tree canopy cover [111]. Blue spaces like urban lakes can improve air quality by cooling

(reducing ozone formation) and by increasing local humidity (which can suppress some particulates) [108]. However, water bodies might also increase humidity to the point of discomfort in tropical cities, which is a factor to manage. Overall, the environmental amelioration pathway of green/blue space is well-documented: greener cities have better air quality metrics and lower summer temperatures, which in turn lead to healthier residents with fewer heat strokes, asthma exacerbations, and related illnesses [112].

Nature's contributions to social well-being and safety are increasingly recognized. Green and blue settings often serve as community hubs that foster social cohesion. They are places where neighbours meet, children play together, and community events are held. This increased social interaction can build trust and collective efficacy in a neighbourhood. A study by Kuo and Sullivan [113] in Chicago public housing found that buildings with surrounding trees and greenery had stronger sense of community and less aggressive behaviour among residents compared to identical buildings without nature. More recent research echoes these findings: a 2019 longitudinal study in Australia found that individuals who moved to neighbourhoods with more green space reported reduced feelings of loneliness over time [114]. Parks provide a venue for social activities (sports leagues, picnics, cultural festivals), which helps reduce social isolation, which is a known risk factor for morbidity and mortality [115]. By facilitating face-to-face encounters, green spaces may indirectly improve mental health through enhanced social support networks. Moreover, there is evidence that greener neighbourhoods experience lower crime rates. Studies in Philadelphia showed that "greening" vacant lots (by cleaning debris, planting grass and trees) led to significant reductions in gun violence and burglary in the surrounding area. One citywide experiment involved randomly assigning some abandoned lots to be cleaned and greened while others were left as-is; areas around the greened lots saw violent crime decrease and residents reported feeling safer and less stressed [116]. Proposed mechanisms include: improved aesthetics and pride in community deter antisocial behaviour, more "eyes on the street" from people using the green space, and the calming psychological effect of nature reducing aggression. A systematic review by Shepley et al. concluded that urban greening generally has either a neutral or crime-reducing effect, especially when community engagement is part of the process [117]. Likewise, increasing street trees and vegetation has been associated with

lower rates of assault, robbery, and property crimes in some studies, though care must be taken that landscaping does not unintentionally provide cover for illicit activity [118]. Blue spaces can also contribute to social cohesion. However, the benefits of blue space for social outcomes are less studied; they likely parallel green space by offering communal recreation areas and landmarks that strengthen community identity [108].

Finally, emerging evidence on microbiome and immune health suggests an intriguing pathway: exposure to biodiverse natural environments may beneficially influence the human microbiota and immune regulation. This idea, sometimes called the “microbiome rewilding” or “Old Friends” hypothesis, argues that modern urban living (with limited contact with soil, animals, and diverse plant life) can lead to less diverse personal microbiota and a higher risk of immune-related disorders (allergies, asthma, autoimmune diseases) [119]. Green spaces, particularly those rich in biodiversity, may increase contact with environmental microbes that train the immune system. For instance, one study found that children attending daycare where outdoor play areas were enriched with forest floor vegetation and soil had more diverse skin and gut microbiota and improved T-cell immune function compared to children in standard paved playgrounds [120]. Another study found that species richness was positively associated with increased Forced Expiratory Volume at the First Second (FEV₁) and Forced Vital Capacity (FVC) [81]. A recent systematic review concluded that greenspace exposure tends to diversify the human microbiome and shift it toward a composition associated with better health (more anti-inflammatory bacterial species) [121]. In adults, levels of beneficial gut microbes have been correlated with residential greenness, suggesting that simply living near vegetated areas might modulate the microbiota through contact with environmental bacteria or by reducing stress hormones that alter gut physiology [122]. Though this field is nascent, small trials have shown that installing green walls or indoor plants can alter the indoor microbiome and perhaps occupant immune responses [123]. Improved microbiome exposure could partly explain findings like lower rates of allergies in rural versus urban children, or why farming communities (rich in microbial contact) have less asthma [124]. It also aligns with salutogenesis: a biodiverse environment can be thought of as salutogenic by continually engaging and balancing our immune system.

The public health implication is that conserving biodiversity in urban parks and designing “wild” play spaces might yield immune benefits for city dwellers.

1.5.3. Green and Blue Spaces and Children’s Health

Children may be especially influenced by green and blue spaces due to their developmental plasticity and the importance of early-life environment for long-term health. Regarding cognitive development, an investigation in Barcelona followed primary school students over 12 months and found that those attending schools with more surrounding green space showed significantly greater improvements in working memory and attention than those at less-green schools [16]. The authors attributed this cognitive boost partly to nature’s ability to reduce ambient air pollution and noise around schools, as well as provide restorative micro-breaks for students’ brains. Another study in London found that less neighbourhood greenery was associated with poorer spatial working memory in 11-year-olds, suggesting that even in dense cities, small differences in greenness can impact cognitive performance [125]. Access to nature may also translate into improved academic performance. Matsuoka found that high schools with abundant trees and views of nature had higher test scores, college attendance rates, and student focus compared to those surrounded by built infrastructure [126]. However, findings are not uniform. A study in Massachusetts schools found a small negative relationship between greenness and academic scores [127].

Green spaces also influence behaviour and behavioural problems. A systematic review concluded that green space exposure was associated with reduced risk of attention deficit hyperactivity disorder (ADHD) and overall behavioural difficulties in children, though most evidence was cross-sectional [128]. A 2022 study linked health insurance records to green space: researchers found that children with more green space within 250 meters of their home had significantly lower odds of being on prescription medication for ADHD. The association was strongest for children in the most economically disadvantaged neighbourhoods and was absent in the wealthiest neighbourhoods [129]. These findings align with experimental studies where short exposures to nature improved attention in children with ADHD. For example, a small

crossover trial showed that a 20-minute park walk produced attention improvements similar in magnitude to those reported for stimulant medication in other studies, and larger than after an urban walk. The prevailing hypothesis is that natural environments replenish directed attention and reduce stress/arousal, which can help children better self-regulate their behaviour and impulses [130].

Still related to behaviour, cortisol measurements of children in outdoor forest classes versus traditional indoor classes show more stable daily patterns and less dysregulation among the nature-exposed children (indicative of lower chronic stress) [131]. Green schoolyards have been associated with improved mood and fewer peer conflicts during recess, as the environment encourages imaginative cooperative play rather than competitive or aggressive interactions [132].

Child respiratory outcomes show the clearest benefits of nature exposure on lung function, with mixed evidence for asthma. In the UK ALSPAC birth cohort, greater residential greenness and the presence of an UGS were associated with small but significant increases in FEV₁ and FVC measured repeatedly from childhood into young adulthood, independent of air pollution and sociodemographic factors [133]. Similarly, a school-based study in Porto found that children attending schools in greener surroundings had better lung function than peers in more built-up areas [134]. By contrast, asthma associations are inconsistent. In Barcelona, overall residential greenness was not related to current asthma, whereas living near parks was associated with a higher prevalence of current asthma [135]. Across Europe, an individual-participant meta-analysis reported better lung function with higher childhood green-space exposure but no consistent association with asthma or wheeze [136]. Evidence on blue spaces and paediatric respiratory outcomes remains limited.

Paediatric cardiovascular findings for green and blue space exposure are emerging but mixed. Cross-sectional cohort analyses in Europe and China link greater greenness to lower blood pressure in school-age children. For example, 10-year-olds in the GINIplus/LISAplus cohorts living in greener neighbourhoods had lower systolic and diastolic BP than peers in less green areas [137], and large school-based studies in China reported lower SBP and lower odds of hypertension at schools surrounded by more

greenness [138]. In Portugal, it was found that children with more neighbourhood green spaces around schools had lower allostatic load, a composite of cardiometabolic and inflammatory biomarkers, suggesting reduced multisystem stress [139]. However, a large meta-analysis did not find consistent associations between residential greenness and cardiometabolic outcomes (including blood pressure and lipids) at school age, underscoring heterogeneity across settings and measures [136]. Evidence for blue spaces and paediatric cardiovascular markers is still limited. Mechanistic reviews suggest blue spaces can promote restoration and physical activity, a pathway relevant to cardiovascular health, but paediatric cardiometabolic data remain sparse [140].

Children's metabolic health also appears to track with vegetation. Several studies find that greener residential environments are associated with lower BMI or smaller BMI increases across childhood, plausibly via higher outdoor play, less sedentary time, and stress buffering [141, 142]. In a study in the USA, children living in greener census tracts showed smaller pandemic-period increases in obesity and lower incident obesity among those not obese at baseline. Effects were clearest in urban/suburban settings, with heterogeneity in rural areas (suggesting vegetation type and usability matter) [143]. Earlier work following U.S. children and adolescents over two years similarly linked neighbourhood greenness to more favourable BMI trajectories, and systematic reviews converge on the conclusion that access to safe, usable green/open spaces supports weight-related behaviours even when findings for BMI per se are mixed [107].

Emerging evidence suggests nature contact can shape immune regulation and the microbiome in young children. In a Finnish daycare intervention, replacing standard play yards with forest floor and biodiverse plantings for four weeks increased skin/gut microbial diversity and up-regulated immunoregulatory markers compared with controls. Although longer follow-up is needed, this provides rare causal evidence that everyday biodiverse environments can beneficially tune immune function in early childhood [120].

Perinatal and early-life outcomes are another pathway through which green and blue spaces may influence children's health. Studies in Spain [144], in Canada [145] and Lithuania [146] report that higher residential greenness during pregnancy is associated

with higher term birthweight and lower odds of adverse outcomes (small-for-gestational-age, preterm birth), even after adjustment for air/noise pollution. In some settings the benefits are strongest among lower-SEP mothers, consistent with a health-equity gradient. Proposed mechanisms include reduced environmental stressors, better maternal mental health, and more opportunities for safe activity.

1.5.4. Equity, Inclusivity, and Vulnerable Populations

Green and blue spaces can advance population health, but access and benefits are uneven. Socioeconomically disadvantaged and marginalised neighbourhoods typically have fewer parks, lower tree canopy, and poorer-quality or less safe spaces [56]. Across many cities, minority communities have markedly less canopy cover even after adjusting for income, and in Europe, immigrants and low-income residents often live in traffic-dense areas with little green buffering [147]. School environments mirror these patterns: poorer districts frequently have asphalt-dominated yards, whereas wealthier schools possess greener campuses [148]. These disparities matter for health. Areas with less greenness often show higher burdens of cardiovascular and mental ill-health [149]. A WHO review frames access to nearby green space as a core equity target that remains unmet for many urban poor [67].

Benefits also vary across groups. Evidence suggests that nature may confer larger relative gains where baseline stressors are high or resources scarce. For example, stronger associations between nearby green space and reduced ADHD medication use have been reported in less affluent settings [129]. Some studies indicate sex- and age-specific responses (e.g., greater stress reduction among women or larger mood benefits for older adults), likely reflecting different patterns of use, social needs, and competing opportunities [150, 151].

Crucially, environmental burdens and amenities are spatially coupled. Lower-income areas are more exposed to air pollution and urban heat, precisely where trees and parks could offer the greatest mitigation. Historical planning decisions, including redlining in the United States, have left lasting legacies of sparse canopy and higher summer temperatures [152]. Targeted greening in these areas can therefore serve as a health equity intervention.

Yet greening can also trigger “green gentrification”: new parks and high-profile amenities may raise property values and living costs, attracting wealthier residents and displacing original communities [153]. These dynamics can erode community networks and restrict who ultimately benefits from new infrastructure [154]. Without anti-displacement measures, well-intentioned projects risk widening health gaps.

Inclusive, equity-oriented greening requires community-driven planning; design that reflects local cultural practices; and a mix of dispersed, modest interventions (street trees, pocket parks, schoolyard greening) rather than singular, catalytic projects that invite speculation [155]. Pairing environmental investments with housing protections helps retain residents who stand to benefit most [156]. Equity tools can guide the prioritisation of park-poor neighbourhoods [157]. Programming free events, supporting local hiring, and offering youth sports, all can strengthen stewardship and ensure spaces serve existing communities. Post-implementation monitoring of demographic and health indicators allows timely policy responses if displacement pressures emerge [156].

1.6. Childhood and Adolescence as a Critical Period in Development

The WHO, in line with the United Nations Convention on the Rights of the Child, defines a child as any individual under the age of 18 years [158]. Within this broad category, further developmental distinctions are often made: early childhood, middle childhood and adolescence. Childhood and adolescence are widely recognised as critical stages in the life course during which environmental experiences can have lasting influences on health and development [159, 160]. In the context of green and blue space exposures, these developmental periods may represent windows of heightened vulnerability and opportunity [17].

1.6.1. Critical vs. Sensitive Periods

Life-course epidemiology and the Developmental Origins of Health and Disease (DOHaD) framework emphasize that the timing of exposures can shape long-term health trajectories [160]. A critical period is defined as a limited time window of rapid developmental change when an exposure (or its absence) can have irreversible effects on structure or function, with little to no effect outside that window [161]. A sensitive period, by contrast, is a developmental window during which an organism is especially responsive to an exposure, but not exclusively so [161]. Sensitive periods begin and end more gradually, and outside these windows the exposure may still exert effects, albeit weaker or requiring stronger doses [161].

Both concepts are integral to DOHaD and life-course theory [160]. The DOHaD paradigm, stemming from the “foetal origins” hypothesis, initially focused on prenatal and early infant phases as critical periods during which nutritional, chemical, or psychosocial exposures can “program” long-term physiology and disease risk [160]. This idea of early “programming” has expanded to include multiple periods across the life span when plasticity is elevated, including gestation, infancy, childhood and adolescence [160]. Life-course scholars now recognize that developmental plasticity (the ability of an organism to adapt structurally or functionally to environmental inputs) extends beyond the first 1,000 days and that later life transitions (such as puberty) may also serve as

sensitive windows for environmental influence [162]. The key implication is that timing matters: exposures to green or blue spaces might confer particularly strong benefits (or, conversely, adversities like pollution or trauma might inflict greater harm) if they occur during specific developmental windows when neural circuits, immune calibration, and health behaviours are being established [17, 163].

1.6.2. Developmental Stages and Trajectories

Human development from conception through adolescence can be divided into several stages, each characterized by distinct physiological and psychosocial changes. These stages represent dynamic trajectories where the foundations of health are laid.

1.6.2.1. Prenatal and Perinatal Programming (Conception to Infancy)

The prenatal period is arguably the quintessential critical period in DOHaD research. During gestation, cells are differentiating into organs, and essential systems are being constructed [164]. This is a time of vulnerability. Maternal exposures such as undernutrition, toxin ingestion, high stress hormones, or infections can disrupt developmental pathways, often with irreversible consequences for the foetus [165]. For instance, maternal stress during pregnancy can influence foetal hypothalamic–pituitary–adrenal (HPA) axis, potentially predisposing the child to heightened stress reactivity and anxiety in later life [166]. Nutritional deficits or toxicants in early gestation may cause permanent organ structure changes, “programming” elevated risks of hypertension or diabetes decades later [167]. Many such findings underpin the foetal programming or Barker hypothesis, which posits that conditions in utero and early infancy can shape later susceptibility to adult disease [160]. Green and blue space exposures during the prenatal and perinatal period have attracted research interest for their potential to buffer stress and enhance birth outcomes. Natural environments may reduce maternal allostatic load (through stress reduction and improved air quality), improving placental function and foetal growth [145]. Higher residential greenness around the maternal residence is associated with significantly lower odds of preterm birth and higher infant birth weight [144]. These benefits are partly attributed to lower

exposure to air pollution and heat in greener areas, as well as the psychological restoration to expecting mothers [144]. Blue spaces are similarly being linked to lower maternal stress levels and healthier birth weights [108].

The perinatal period is also critical: exposures such as mode of delivery, initial microbial colonization, and early bonding experiences can alter a newborn's microbiome and stress reactivity [168]. Natural settings for early mother-infant interactions may subtly influence maternal mental health and breastfeeding success, which in turn affect infant development [67].

1.6.2.2. Early Childhood (0–5 years): Brain Plasticity and Immune Maturation

Early childhood, from birth to around five years, is marked by developmental gains in multiple domains. The brain grows to ~90% of adult volume by age five [169], with an overabundance of neural connections formed in infancy followed by pruning and refinement through toddlerhood [170]. This period of heightened neuroplasticity supports rapid learning of language, emotional attachment, motor skills, and basic cognitive schemas [171]. The young child's brain creates synapses rapidly. By age two or three, synaptic densities in some regions exceed adult levels, after which a wave of synaptic pruning sculpts neural circuits based on experience [170]. During these early years, children's immune and metabolic systems are also maturing [172]. The immune system learns to distinguish self from non-self, building a repertoire of antibodies and regulatory cells; exposures to diverse microbes help "train" immunoregulation and prevent inappropriate inflammation [119]. The gut microbiome, enriched via breastfeeding, diet, and environment establishes by approximately age three, influencing digestion and immune tolerance [172].

This plasticity makes early childhood a sensitive period in which environmental conditions can leave profound imprints [173]. A stimulating, nurturing environment rich in play, language, and exploration supports optimal brain development [171], whereas extreme deprivation or toxic stress can disrupt neural and endocrine development with lasting impacts on learning and mental health [173]. Nature exposure is thought to be

particularly beneficial in early childhood because it engages multiple senses, encourages physical activity, and promotes stress reduction during a key window of brain and immune development [162]. Young children allowed to play in green settings often exhibit better motor skill development and aerobic fitness than those confined to indoor or barren environments [174]. There is also evidence that contact with natural environments early in life bolsters immune maturation: a study found that toddlers at daycare centres where the playground was “greened” (covered with grass, soil, and planter boxes) showed an increase in circulating regulatory T cells and anti-inflammatory cytokine levels after just one month, compared to children in standard asphalt playgrounds. The microbiota on their skin and in their guts became more diverse and shifted toward a composition associated with healthy immune function [120]. These findings suggest that early childhood nature exposure may shape the developing immune system, potentially lowering risks of allergies and other immune-mediated disorders [120].

Early childhood is also when foundational emotion regulation and stress-response patterns are established [173]. Frequent access to green space may support young children’s psychosocial development by providing safe but stimulating venues for imaginative play, exploration, and self-directed discovery [162]. Natural environments tend to elicit curiosity and reduce overstimulation, helping young children develop attention control and calmness [175]. Evidence directly focused on stress buffering by nearby nature in toddlers and preschoolers remains more limited. However, findings from older children support the plausibility of this pathway across childhood and provide a bridge to the following developmental stage. In a study of rural school-aged children, Wells and Evans demonstrated that higher levels of vegetation around the home moderated the impact of stressful life events on children’s psychological well-being. Nature acted as a buffer, so children with greener surroundings coped better with adversity than those in less green settings [176].

1.6.2.3. Middle Childhood (6–12 years): Social Skills and Physical Activity Patterns

Middle childhood is often considered a latent period of steady growth and skill consolidation, following the tumult of early development and preceding the upheavals of adolescence. During this stage, children's cognitive abilities (such as logical reasoning, attention span, and self-control) expand significantly, and they gain greater independence in navigating their environment. It is a critical time for socialization, as peer relationships deepen and children learn to cooperate, negotiate, and empathize with others [171]. Patterns of physical activity and play established in middle childhood can carry into adolescence and adulthood; for example, children who develop active lifestyles and sports participation by age 10 are more likely to remain active later on [177]. Likewise, dietary habits and recreational preferences formed in this period can influence long-term health [178].

Although the biological growth rate is slower than in infancy or adolescence, middle childhood is still a sensitive time for developing healthy behaviours and coping skills. The brain undergoes a second wave of synaptic pruning, particularly in the prefrontal cortex, toward the end of this period [169], which refines executive functions like planning and impulse control in preparation for adulthood. Children's academic and attentional capacities also mature greatly during these years. In this context, green and blue spaces play a role in supporting both physical and cognitive development. Evidence shows that school-age children with greater access to green spaces have better attention and working memory than those with more limited nature access. A longitudinal study in Spain found that those attending schools with more surrounding greenness showed significantly greater improvements in working memory and attentiveness over one year, compared to peers in less green schools. The benefits for cognitive development were partly mediated by reduced exposure to air pollution at the greener schools [16]. Similarly, a systematic review of paediatric studies concluded that green space exposure is associated with better cognitive performance and can restore directed attention in children, helping to reduce mental fatigue [179]. These findings align with Attention Restoration Theory, which posits that natural environments replenish the capacity for focused attention more effectively than built environments [86].

Middle childhood is also when children typically gain more freedom to roam locally, especially by the upper end of this age range. Safe access to green spaces can encourage more physical activity and play, helping to establish active routines. Indeed, greenness around the home and school has been linked to higher levels of moderate-vigorous physical activity in children and lower rates of childhood obesity [174]. A review by Bikomeye et al. noted that access to green schoolyards was consistently associated with increased physical activity during recess and after school, with potential spillover benefits for BMI and fitness [179]. Socially, natural play spaces often provide more diverse and imaginative play opportunities than standard playgrounds, which can improve cooperation and reduce aggression [174]. Some studies report that greened schoolyards promote supportive social interactions and reduce bullying, as children engage in more creative group play in nature-rich settings [179].

1.6.2.4. Adolescence (13–18 years): Hormonal Shifts, Identity Formation, and Peer Networks

Adolescence is a period of profound transformation bridging childhood and adulthood. Biologically, the onset of puberty brings a surge of sex hormones (oestrogen, testosterone) that drive the development of secondary sexual characteristics, a growth spurt, and maturation of reproductive capacity [180]. These hormonal changes also affect brain function and can influence mood and behaviour. The adolescent brain undergoes a final phase of remodelling: earlier overproduced synapses are pruned with remarkable specificity (up to 50% of synaptic connections in some regions are eliminated during adolescence) while myelination accelerates, particularly in frontal brain regions and circuits connecting different brain areas [169]. The result is a more efficient but somewhat less malleable adult brain by the early 20s. Notably, prefrontal cortical regions, responsible for executive functions and impulse control, are among the last to fully mature, whereas limbic regions tied to reward and emotion are highly active in mid-adolescence. This developmental mismatch partly explains why adolescents may show heightened risk-taking, sensation-seeking, and peer-influenced decision-making [181]. At the same time, the adolescent brain retains considerable plasticity, more so than in

mature adulthood, offering a “second window” of opportunity for environmental influences to shape neural pathways [182].

Psychosocially, adolescence is characterized by a quest for identity formation and increasing autonomy. Teens begin to solidify their personal values and aspirations, often experimenting with different roles [183]. Peer relationships take on heightened importance. Peer approval can strongly sway behaviour, and social networks expand [184]. Emotional reactivity can be intense, as adolescents learn to regulate new feelings of romantic love, stress, and existential contemplation. It is also a time when mental health issues such as depression, anxiety, or risky behaviours often emerge or peak, likely due to the confluence of biological changes and social pressures [185].

In this dynamic context, exposures to green and blue spaces may serve as important protective and developmental assets for adolescents. The benefits of nature for stress reduction and mental health are well documented in adults, and emerging evidence suggests that adolescents may be uniquely responsive to nature contact as well. For instance, a nationwide population-based cohort study in Denmark found that adolescents who grew up with the lowest levels of green space had significantly higher risks of developing psychiatric disorders by young adulthood, whereas those with greener childhood environments (especially sustained through adolescence) had lower risk of disorders such as depression, mood disorders, or substance abuse disorders [17]. This points to adolescence as not only an outcome period but also potentially a sensitive period for building resilience against mental illnesses. Indeed, a recent longitudinal study in the United States (covering ages 2–18) observed that residential green space was associated with fewer internalizing symptoms (anxiety, depression) only in early childhood, not in middle childhood, but the authors hypothesize that impacts in adolescence and early adulthood might re-emerge in later assessments [163]. The idea is that adolescence could represent a second window when new domains of mental health (identity, autonomy, social belonging) become salient and might be influenced by environmental support or stress.

Nature may support adolescents in several interrelated ways. First, natural settings can provide a refuge from stress and a context for emotion regulation during a tumultuous life

stage. Qualitative studies report that teens often use green or blue spaces (such as a quiet park, a beach, or even a tree-lined street) as a place to calm down, reflect, or escape social pressures. This is consistent with nature's known stress-mitigating effects (e.g. reducing cortisol and sympathetic activation) [175]. Second, challenging outdoor experiences can promote self-esteem, confidence, and teamwork in adolescents. Programs like wilderness therapy and adventure education leverage the adolescent proclivity for novelty and risk by providing safe risks in nature like rock climbing, backpacking, or whitewater rafting that build resilience and coping skills [186]. Evaluations of wilderness adventure programs have shown improved psychological outcomes in youth, including increased self-efficacy, better problem-solving and perseverance, and even re-engagement with school among previously disengaged teens [186]. Participants often report transformative personal growth from overcoming challenges in the outdoors, which can translate to greater resilience in the face of life's obstacles. Third, green and blue spaces offer constructive outlets for peer interaction and identity exploration. Many adolescents congregate in parks, sports fields, or skate areas, and these physical environments can either facilitate healthy socialization or, if unsafe/absent, contribute to negative behaviours. A well-designed skate park or a community garden, for example, can channel teenage energy into skill-building, positive peer networks, and community engagement, steering youth away from harmful activities [187].

1.6.3. How Children can be influenced by Green and Blue Spaces

Nearby nature alters both the internal context of the child, like arousal, inflammation, immune calibration, sleep timing, and the external context in which development unfolds, like air, heat, noise, light, and social affordances [5]. These potentials are then converted into everyday routines through play, peer interaction, school design, and family and community practices. The logic is cumulative and mutually reinforcing rather than linear: small, repeated moments of restoration and engagement compound into durable differences [72].

A natural starting point is stress physiology and attention. Environments rich in living features such as trees, water, textured ground, shifting light, tend to dial down sympathetic arousal and permit parasympathetic recovery [188]. That adjustment shows within minutes as slower heart rate, lower blood pressure, calmer affect, and a more open attentional stance [188]. For school-age children expected to sustain directed effort in noisy, demand-heavy settings, these brief resets help restore the capacity that classroom tasks deplete. Seen from this angle, better on-task behaviour and fewer disruptive episodes in greener school contexts are the behavioural face of a stress system that is being allowed to cycle between effort and recovery instead of being held at high idle all day [189].

Stress chemistry entwines with immune regulation, which is still calibrating in early childhood. Repeated relief from arousal loosens the coupling between daily hassles and low-grade inflammation, while contact with biodiverse outdoor substrates like soil, plants, and bioaerosols, can broaden microbial exposure in ways that can nudge developing immune responses toward tolerance and balance [119]. The daycare yard experiments are important: they suggest that modest shifts in everyday biodiversity can reshape skin and gut communities and up-regulate immunoregulatory markers over weeks, offering a plausible bridge from short-run environmental change to longer-run differences in allergy risk, infection patterns, or inflammatory tone [120]. All this just requires frequent, ordinary contact with living materials during years when the immune system is especially plastic [119].

Nature also works by softening environmental loads that routinely limit children's capacity to thrive. Vegetation filters particulate matter and traps dust, taking some of the respiratory burden off developing lungs and the cardiovascular system that supports them [111]. Trees and shade structures cool playgrounds, courtyards, and walking routes, reducing heat stress that otherwise erodes mood, attention, and willingness to be active [190]. Planted buffers and varied ground surfaces dampen and diffuse noise, a ubiquitous exposure linked to sleep disruption and learning problems [50, 191]. When air is cleaner, temperatures are tolerable, and noise is buffered, classroom instruction is less taxing, recess is restorative rather than agitating, and active travel or outdoor play feel inviting rather than punishing. In parallel, daylight exposure helps entrain circadian

rhythms via melatonin cycling. Children who spend time outside typically fall asleep more readily and keep steadier sleep–wake schedules [192]. Because sleep regulates attention, mood, appetite, and cardiometabolic processes, small increases in predictable daylight and outdoor time can echo through many health outcomes.

Then there are the behaviours that accumulate and translate into health. Attractive, nearby, and safe green spaces make active commuting to schools more likely, leading to lower BMI [193]. Gardening at school or with family can tilt diet toward fresh produce [194] while also embedding routines of time outside and light activity. Access to calming outdoor refuges supplies non-screen coping options when children are dysregulated or bored [132, 195]. None of these behaviours needs to be perfect to matter. What matters is that the cues children encounter all day, from the path to school, the look and feel of the yard, the destination for a short family walk, all repeatedly nudging choices toward recovery, activity, daylight, and social contact.

Development determines how those cues are taken up. Early childhood thrives on sensorimotor and constructive play. Natural settings provide “loose parts” and varied terrain that invite self-set challenges and reward persistence with quick feedback and visible mastery. These micro-challenges build coordination and early executive capacities without exhausting attention, and because children choose them, effort alternates naturally with rest in the very pattern the stress system is built to follow [196]. In middle childhood, play becomes more rule-bound and collaborative. Heterogeneous landscapes like open fields, shaded edges, climbable structures, garden patches, allow multiple games to coexist, which reduces crowding and conflict and brings quieter or less assertive children into the action. Cooperative tasks arise organically when the environment itself suggests them [197]. For adolescents, a biologically heightened appetite for novelty and challenge can be channelled into supervised adventure that builds competence, self-efficacy, and fitness without courting harmful risk.

None of these pathways operates uniformly. Access and quality work as gatekeepers: canopy cover, safe paths, inviting and well-maintained features, and purposeful programming determine whether potential benefits are realized [198]. Safety, regardless of being perceived or real, mediates whether parents allow independent mobility and

whether older children choose parks over indoor options; parental safety perceptions, traffic exposure, and conflict on crowded courts all shape children's use of outdoor spaces [199]. Socioeconomic context matters because baseline stress and environmental burdens are often higher where resources are scarcest; at the same time, disadvantaged neighbourhoods tend to have lower-quality and less accessible parks, and often less tree canopy and higher heat burdens, sharpening inequities in exposure and in the feasibility of outdoor routines [56, 147, 152]. Age and sex differences also appear as affordances and preferences shift. Diversifying schoolyards beyond ball courts and adding naturalized "loose-parts" zones can broaden participation for girls and younger children and reduce crowding-related conflict [200]. Climate and season also set practical boundaries. In hotter cities, shade trees and other thermal refuges are prerequisites for outdoor time, and heat itself undermines learning and comfort. Designing for shade and permeable, cooler surfaces keeps nature playable year-round and protects the very attentional and behavioural gains schools and families seek to foster [48, 201].

1.7. Knowledge Gaps

Although the literature linking children's health to contact with green and blue spaces has expanded, some gaps still limit theoretical progress and policy design. These gaps cut across study design (when and for how long children are exposed), context (where exposure actually happens), measurement (what kind of nature and with which qualities), and mechanisms (how benefits are conferred).

First, the field still leans heavily on cross-sectional designs, which makes it difficult to identify when exposure matters most and whether benefits accumulate over time. Childhood is not homogeneous, there are specific changes in specific periods, with some being sensitive and/or critical. The few longitudinal analyses that follow children across multiple stages suggest timing and persistence matter. Implications that are central to a life-course perspective but still under-tested at scale [17].

Design limitations are compounded by where exposure is measured. Most studies derive exposure at the residence, but children also spend a large portion of their days at school. Evidence that school-area greenness relates to cognitive development (with traffic pollution acting as a partial mediator) illustrates why moving beyond home buffers matters [16]. Conceptually, the Uncertain Geographic Context Problem makes this point explicit and motivates designs that incorporate school locations among others [202].

Another imbalance concerns the spaces that are studied. Green spaces dominate, while blue spaces receive comparatively little attention in child health research. In countries like Portugal this can be particularly relevant since coastal and riparian environments are prominent features of many settings, so understanding whether water-related settings carry distinct psychological or physiological benefits can be directly policy-relevant. Systematic reviews still lack evidence regarding child/adolescent evidence and call for more rigorous, context-sensitive studies of blue spaces [108, 203].

Age also matters for how these spaces are used. Adolescents often engage with them for socializing, identity formation, and respite. Without attention to perceived safety, programming, and design qualities that resonate with adolescents, interventions risk underuse or inequitable uptake, especially in Southern European settings [204].

Measurement choices remain a further constraint. Satellite-derived indices such as NDVI are invaluable but alone they cannot distinguish vegetation structure (e.g., canopy versus grass), tend to saturate in high-biomass contexts, and say little about accessibility, safety, or maintenance [205]. When possible, feature-level metrics (e.g., tree canopy), and accessibility/quality indices, can complement greenness proxies [206].

Finally, plausible mechanisms remain under-tested in paediatric populations. Frameworks posit mitigation (air pollution, heat, noise), restoration/stress pathways, physical activity, and social cohesion, but formal mediation analyses are still scarce and methodologically heterogeneous [5].

2. OBJECTIVE

The main research question of this thesis is: In what ways do green and blue spaces benefit children's and adolescents' health, and how can we promote their use?

To address this broad question, four specific objectives were set.

1. To assess the association between the life-course exposure to green spaces and blue spaces and intelligence in children with 10 years of age, and to examine the roles of the potential mediators (paper I – published);
2. To assess the association between the life-course exposure to green spaces and blue spaces and respiratory function in children with 10 years of age, and to examine the roles of the potential mediators (paper II – published);
3. To assess the association between the life-course exposure to greenness and behaviour problems in children with 7 years of age, and to examine the roles of the potential mediators (paper III – submitted);
4. To explore, using focus groups, the perspectives of adolescents regarding their use of green spaces as well as the perceived benefits and preferences (paper IV – published).

3. METHODS

3.1. Study Design

This thesis encompasses three quantitative studies and one qualitative study. The quantitative studies are observational analyses nested in the G21 [207, 208]. Each quantitative study focuses on a distinct outcome, but they share core methodological principles, including a life-course exposure assessment and use of cohort data. The qualitative study is also nested in G21 and designed to explore adolescents' perceptions and use of green spaces through focus group discussions. By integrating findings from both quantitative and qualitative approaches, this thesis adopts a comprehensive perspective to understand the statistical associations between green and blue space exposures and health, and also the lived experiences and preferences of youth in these environments.

Each quantitative study examines exposures measured over time and an outcome measured at a specific age. The behavioural problems study assesses exposures from birth to age 7 in relation to behaviour at 7 years. The intelligence study examines exposures from birth to age 10 and intelligence measured at 10 years. The lung function study similarly considers exposures from birth to age 10 and pulmonary function at 10 years.

The qualitative study employs a focus group design to gain in-depth insights into how adolescents aged between 15 and 16 years use and value green spaces. This design was chosen for its strength in capturing personal opinions as well as the interactive generation of ideas among peers [209]. Focus groups are particularly suitable for engaging youth, who may feel more at ease sharing thoughts in a group setting than in one-on-one interviews [210].

3.2. Population and Data Sources

All participants for the quantitative analyses were drawn from the G21. G21 is a population-based cohort that enrolled newborns and their mothers in 2005–2006 from

all five public maternity units in the Porto Metropolitan Area, which accounted for approximately 95% of the region's births [208]. In total, 8647 infants (born to 8495 mothers) were recruited at birth after 91% of the invited families agreed to participate [207]. The cohort has been followed at multiple time points: at ages 4 years (wave 2, n=7459), 7 years (wave 3, n=6889), 10 years (wave 4, n=6392), 13 years (wave 5, n=4643) and 18 years (wave 6, ongoing). Data collected include comprehensive health assessments, questionnaires for the participants and the caregivers, and information regarding addresses of the residence and school (from 7 years onward).

For each quantitative study, a specific subset of the cohort was defined based on outcome data availability and relevant exposure period. In the behavioural problems analysis, the population included children who participated in wave 3 and were living in the Porto Metropolitan Area at that time. A total of 6269 children met these criteria and had information on behavioural outcomes at 7 years. In the intelligence study, the sample consisted of children who underwent an intelligence assessment at wave 4 (which was a subset of the cohort) and had consistently resided in the metropolitan area throughout their childhood. After excluding those lacking the outcome or living outside the Porto Metropolitan Area at any moment of the evaluations, 3827 children were included for analysis. The lung function study sample consisted of 3278 children who had lung function measured at wave 4 (which was also a subset of the cohort) and always lived in the Porto Metropolitan Area.

The qualitative focus group study drew its participants from G21. At the time of recruitment (early 2022), cohort members were between 15 and 16 years old. Eligibility for the focus groups was restricted to adolescents residing in urban areas of the Porto Metropolitan Area. This criterion was applied to capture experiences in predominantly UGS and to exclude those living in rural settings where exposure to large natural or agricultural green areas might differ substantially. From the pool of eligible G21 adolescents, participants were selected by purposive stratified sampling based on SES. Using data on household income and neighbourhood deprivation [57], all candidates were stratified into SES quintiles. Participants were then randomly chosen from the highest and lowest quintiles to ensure a contrast of perspectives from more disadvantaged vs. more privileged backgrounds. The recruitment aimed for a balanced

representation of genders as well, given evidence that green space use and perception can vary by gender [211]. Invitations were extended by phone to the adolescents' legal guardians, during which the study objectives and procedures were explained and consent was asked from the caretakers and assent from the adolescents. Ultimately, 34 adolescents (roughly equal girls and boys) took part in the focus groups. This sample size was determined by thematic saturation [212].

3.3. Exposure Assessment

Residential address information was updated at each follow-up contact via caregiver interviews or telephone updates. These addresses served as the basis for environmental exposure assessment. All addresses were processed and geocoded using geographic information systems following strict geoprivacy protocols to ensure participant confidentiality [213].

The exposure to green and blue spaces was conducted using different geographic indicators. All exposure measures were derived for the vicinity of the child's residence. In the study of intelligence, exposures were also characterized around the school environment.

The amount of vegetation was quantified using the NDVI, a satellite-derived index of live green vegetation. NDVI is calculated from surface reflectance in the red and near-infrared spectral bands, producing values between -1 and 1 (where more positive values indicate denser vegetation). For each child's residential address, the mean NDVI within circular buffers of 100 meters, 250 meters, and 500 meters radius was extracted. These buffer distances were chosen to represent immediate neighbourhood greenness as well as greenness in the broader surroundings, consistent with prior studies linking residential greenness with health [16]. NDVI was computed using remotely sensed imagery from the Landsat 5 Thematic Mapper (TM) and Landsat 8 Operational Land Imager (OLI) satellites (30 m resolution). To capture peak growing season vegetation, the images from spring/summer months were used, cloud-free ($\leq 5\%$ cloud cover) scenes for the time windows corresponding to the cohort assessments. For each time point, the NDVI in

each buffer was averaged across any available scenes in that period. Any pixels with negative NDVI (indicating open water) were excluded so that the index reflected vegetated land cover only, as in other investigations [214, 215].

In the behavioural problems study, greenness assessment also included measures differentiating vegetation structure types, namely the percentage of the area around each residence that was covered by tree canopy vs. non-tree vegetation vs. no vegetation. These metrics were obtained from the Moderate Resolution Imaging Spectroradiometer (MODIS) Vegetation Continuous Fields product, which provides estimates of fractional land cover by tree canopy and non-tree vegetation at 250-meter resolution. The same buffers as for NDVI were used. Non-vegetated area percentage was defined complementarily (100% minus the sum of tree and non-tree vegetation percentages).

The access to formal UGS such as parks, public gardens, and other nominated green areas was also assessed. Using digital maps obtained from municipal authorities in the Porto Metropolitan Area, 662 public and freely accessible green spaces in the region were included [139]. For each child's residence at each time point the following measures were computed: (a) availability of UGS indicating whether at least one public green space was present within 400 meters or 800 meters from home (yes/no); (b) number of UGS within 400 meters and 800 meters; and (c) distance to the nearest UGS measured as the distance from the residence to the closest UGS. For parks that were fenced or had controlled entries, distance was measured to the nearest official entrance; for open parks, distance was measured to the nearest boundary point [56].

The exposure to blue spaces (major water bodies) was measured using the distance to the nearest significant blue space. The Portuguese national "Atlas of Water" (Atlas da Água) and hydrological maps from the National Water Resources Information System were used to identify relevant blue spaces in the study area, specifically the Atlantic coastline and the major rivers. Only substantial natural water bodies were included. Small features like ponds or fountains were not considered. At each time point, the Euclidean distance to the nearest major blue space was calculated.

3.4. Outcome Measures

We investigated a range of child health and development outcomes, each measured with validated instruments or protocols at the relevant follow-up age in G21.

Child behavioural problems were assessed through parent-report questionnaires when children were 7 years old. Caregivers were asked whether they or the child's teacher had ever suspected the child had problems in several domains, including "impulsivity, hyperactivity, aggressiveness". This question was part of a broader structured questionnaire covering learning, attention, language, socialization, and behaviour issues. The response options were Yes/No for suspected problems in each domain. While it relies on subjective report, it reflects real-world concerns that can lead to reasonably accurate referral decisions [216].

Intelligence was measured at 10 years of age using the Wechsler Intelligence Scale for Children – Third Edition (WISC-III). This is a standardized and widely used test of child intelligence, administered by trained psychologists in a controlled setting [217]. The Portuguese version of WISC-III, validated for use in this population [218], was employed to ensure cultural and linguistic appropriateness. The WISC-III yields several scores; three were used in the study namely the Global IQ, as well as the Verbal IQ and Performance IQ subscales for a more nuanced analysis. The test provides age-normed IQ scores (mean of 100, standard deviation of 15). All testing was done in person during the cohort's 10-year evaluation wave, typically in a quiet room at the research clinic or participant's school, following standardized test protocols. The resulting IQ scores were treated as continuous outcome variables in analyses.

Respiratory health was evaluated at 10 years of age via spirometry, measuring lung function parameters according to American Thoracic Society/European Respiratory Society guidelines [219]. Trained technicians conducted spirometry tests using portable Micro 1 Medical Spirometers (MIR MiniSpir device). Key pulmonary function indicators included: FVC which represents the volume of air (in litres) exhaled after a full inhalation, reflecting lung volume; FEV₁ which represents the volume of air exhaled in the first second of the FVC manoeuvre, indicating airway calibre and resistance; and Forced

Expiratory Flow Between 25% and 75% of Forced Vital Capacity ($FEF_{25-75\%}$) reflecting the average flow rate during the middle half of the exhalation, reflecting small airway function. For each child, multiple spirometry trials were performed to ensure reproducibility. Results were reviewed by a pulmonologist to confirm that they met quality criteria. Lung function measures were expressed as percent predicted values based on the Global Lung Function Initiative 2012 reference equations [220]. This means each child's raw FVC, FEV_1 , and $FEF_{25-75\%}$ were converted into a percentage of the expected value for a child of the same age, sex, and height (with 100% being the reference norm). Using percent-predicted (or equivalently z-scores from Global Lung Function Initiative (GLI)) accounts for natural growth-related increases in lung volumes and allows comparison across individuals. In the analysis, these lung function outcomes were treated as approximately continuous variables. Higher values indicate better lung function.

3.5. Qualitative Data Collection

The qualitative study focused on the themes and insights emerging from adolescents' discussions about green space. The focus groups elicited rich descriptive data on three broad topic areas: (1) modes of green space use – how often and in what ways adolescents use parks or other green areas; (2) perceived benefits of green spaces – youths' views on how green space access affects their well-being, health, or daily life; and (3) preferences and ideal park features – what characteristics of green spaces appeal to adolescents, including design elements, amenities, location, and management, as well as perceived barriers to use. These focus group conversations were transcribed and analysed qualitatively to identify common modes of use and divergent opinions. The results are presented as thematic findings (with illustrative quotes).

3.6. Covariates

Each quantitative study adjusted for a range of covariates to isolate the association of exposures with the outcomes of interest. Covariate selection was guided by prior literature and directed acyclic graph (DAG) conceptual models [221], aiming to account for variables associated with both where families live (and thus their environmental exposures) and the child health outcomes. SES and urbanicity were important to control, since greener environments are often inequitably distributed and SES can independently affect health and development [5, 222].

Sex is a standard covariate because it can influence behavioural problem rates, intelligence test performance, and lung volumes. For instance, boys have higher rates of hyperactivity diagnoses on average [223], and by age 10 boys also tend to have slightly higher lung volumes than girls [224]. Thus, sex was included as a binary control variable in each model.

In most analyses, the children were nearly the same age, but for lung function, age was also adjusted for (in months) at the time of the spirometry test.

Maternal education was used as a key indicator of family SES. Maternal education was reported in years of schooling and categorized into three levels: primary education (up to 9 years of schooling, corresponding to International Standard Classification of Education (ISCED) 0–2), secondary education (10–12 years, ISCED 3), and tertiary education (>12 years, ISCED 4–6). Maternal education is strongly linked to child health and developmental outcomes [225]. The choice of maternal education rather than paternal education was due to higher missing rate in paternal education (10% missing) compared to maternal (<1% missing), and maternal education tends to be highly correlated with paternal education in two-parent families [226].

Monthly household income was reported in categories and also used to represent SES. Participants were grouped income into three brackets: ≤ €1000 per month, €1001–1500, and > €1500. These cut-offs roughly divide the cohort into lower, middle, and higher income families. Income can capture aspects of material resources not fully captured by education, and it may confound associations if, for example, higher-income families both

afford homes in greener neighbourhoods and have children with better health due to other advantages.

To account for community-level disadvantage, an index of neighbourhood deprivation was included. The EDI was included at the census tract level (each tract ~300 households), with higher EDI values indicating more deprived areas [57]. This index is derived from multiple census indicators (e.g., unemployment, low education, housing conditions) and calibrated to the Portuguese context. Because neighbourhood deprivation could influence both the presence of green spaces (urban planners may invest less in green infrastructure in deprived areas) and child health (via numerous social stressors), it was an important covariate to include. It was treated as a continuous variable.

To adjust for the degree of urbanicity of the child's environment two different measures were used across the studies. In all the analyses, population density (number of inhabitants per square km in the census tract, from the 2011 national census) as a continuous measure was used. In the intelligence study, a categorical urbanicity classification was applied (predominantly urban, moderately urban, or predominantly rural parish) based on official definitions for Portugal [227]. Both serve to distinguish children in city-centre high-density settings from those in suburban or rural settings.

In the intelligence analysis, the type of school (public vs. private) at age 10 was used as an additional covariate. School type can be a proxy for socioeconomic background and educational quality: children in private schools in Portugal often come from higher SES families and may have different academic stimulation, which could influence IQ scores [228]. Moreover, school type might relate to school environment differences (e.g., school greenness or resources).

Some variables were conceptualized as potential mediators rather than confounders, but their analysis differed by study. All quantitative studies included child's physical activity and NO₂. Physical activity was measured via parent report (whether the child regularly engaged in any organized physical activity outside of school, Yes/No) [229]. Outdoor NO₂ pollution (µg/m³) at the residential address was estimated using the European Environment Agency's AirBase data (1 km² resolution maps derived from land-

use regression and monitoring stations). NO₂ was selected as the primary pollutant because it is the standard traffic-related marker with stronger intra-urban spatial gradients, yielding better neighbourhood-scale exposure contrast than PM_{2.5} and also showing independent health associations beyond co-pollutants [230, 231]. Each child was assigned the NO₂ concentration of the grid cell of their residence [232]. Both physical activity and NO₂ were included in lung function models to adjust for their direct effects on lung development. Furthermore, the behavioural problems study included also PM_{2.5} as another pollutant and considered two additional mediating factors: sleep duration and maternal mental health. Both have been hypothesized as pathways linking natural environments to child behaviour [72, 233]. The nightly sleep duration at age 7 was derived from parent reports of typical bedtimes and wake-up times on weekdays and weekends (calculated as a weighted average of the hours of sleep per night). Maternal mental health was assessed using the Hospital Anxiety and Depression Scale (HADS), a validated questionnaire completed by the mother [234]. The combined HADS score (sum of anxiety and depression subscales) was used as an indicator of maternal psychological distress.

3.7. Analytical Strategy

Each quantitative study used regression modelling to estimate the association between environmental exposures and the health outcome, adjusting for the covariates described. The model type depended on the outcome distribution: for behavioural problems (binary outcome) logistic regression, and for IQ and lung function (approximately continuous outcomes) linear regression models. Results are presented as odds ratios (OR) for binary outcomes and beta coefficients (mean differences) for continuous outcomes, with corresponding 95% confidence intervals.

Because children in the cohort may share contexts, hierarchical models were used. In the intelligence study, children are nested at both neighbourhood and school levels. A multilevel linear model with random intercepts for neighbourhood (census tract) and school level was used to correctly model the dependency and avoid underestimating standard errors. This approach adjusts for the non-independence of observations within

schools and neighbourhoods and captures residual between-cluster variability (e.g., school quality or local community characteristics) [235]. Multilevel models were not used for lung function and behavioural outcomes because intraclass correlation was near 0 with tiny clusters, random effects were non-identifiable (non-convergence/boundary estimates), and cluster-robust standard errors produced the same confidence intervals.

A variety of exposure variables were examined as well as multiple outcome metrics. Rather than attempt a single combined model with all exposures, separate models were analysed for each exposure–outcome pair, given the high collinearity among certain exposure measures. For example, NDVI in 100 meter vs. 250 meter buffers were strongly correlated. Including both in one model would create multicollinearity issues. Instead, independent models were fitted and each coefficient interpreted as an isolated association. Interpretations were cautious and did not rely on formal multiple comparison corrections, instead basing conclusions on consistency and strength of evidence across related metrics.

A key analytical innovation in two of the studies (behavioural problems and lung function) was the incorporation of life-course exposure patterns. Beyond using the average exposure from birth to outcome age, early-life exposure and changes in exposure over time were disentangled. A two-step modelling procedure was used [236]:

1. Exposure Trajectory Estimation (Step 1): For each child, longitudinal exposure data was modelled as a function of age. Specifically, an individual linear regression of exposure on age for each child. This yields two parameters: an intercept, representing the model-predicted exposure level at the starting point (birth); and a slope, representing the change in exposure over time for that child. For dichotomous exposure variables (like presence of a park within 400 meters, which can flip from no to yes), a logistic model was used to estimate probability trends, but for continuous exposures (NDVI, distances) a linear model was used.
2. Outcome Regression with Trajectory Metrics (Step 2): Those person-specific intercepts and slopes were then used as predictors in the health outcome regression model.

The standard errors of the intercept and slope from Step 1 were also used in the outcome model as additional covariates.

Using this life-course approach, three sets of models were studied for each outcome: one using averaged exposure over time, one using intercept (early exposure), and one using slope (exposure trend over time) as predictors. This allowed to assess which aspect of exposure was most influential.

Additional analyses were conducted to investigate potential mediators. In the IQ study, a simpler mediation assessment was conducted. After finding a significant association between certain green space metrics those models were adjusted adding the child's physical activity or NO₂ level into the regression. Then the percentage of effect explained was calculated by the mediator using the formula: % mediated = $[1 - (\beta_{\text{exposure adjusted for mediator}} / \beta_{\text{exposure original}})] \times 100$ [237]. This approach quantifies mediation in an intuitive way, though it assesses one mediator at a time and assumes no mediator-outcome confounding. In the behavioural problems and lung function studies, mediation analysis was conducted using structural equation modelling (SEM). This allowed to simultaneously model the direct effect of green space on the outcome and indirect effects through one or more mediators. In the behavioural problems study, due to the binary nature of the behaviour outcome, a weighted least squares estimator was used with mean and variance adjustment in the SEM, which is appropriate for categorical outcomes [238]. Indirect effects (mediation effects) were tested for significance, and standardized path coefficients were examined. The SEM approach is advantageous because it can handle multiple mediators concurrently and provides formal significance tests for indirect effects.

Effect modification was tested across subgroups for key characteristics such as sex and SES. In the IQ study, interaction terms between green space exposure and child's sex, mother's education, school type, and neighbourhood deprivation index were assessed. Similarly, the lung function study tested interactions with sex and SES indicators. These were evaluated via likelihood ratio tests comparing models with and without the interaction term. No statistically significant interactions were detected in those studies. Thus, results were presented for the whole sample without stratification [239].

Missing data was handled differently in the different studies. In the behavioural problems study, about 14% of children had some missing information on covariates or mediators. In this study, multiple imputation by chained equations were employed. Twenty imputed datasets were generated under the assumption of data missing at random [240]. Estimates from the 20 datasets were combined using Rubin's rules to produce final coefficients and standard errors. A complete-case analysis (excluding all missing data) as a sensitivity check was also studied. In the lung function and IQ studies, the proportion of missing data was low for the main variables after excluding those without the outcome. A complete-case analysis in these studies was used.

The focus group discussions were analysed using thematic analysis, following a hybrid deductive–inductive approach [241]. It started with a coding framework informed by existing literature on adolescent green space use and the specific research questions. This served as a deductive code tree. After the focus groups, all recordings were transcribed. Transcripts were then imported into NVivo qualitative analysis software for coding. Two researchers independently coded the first two focus group transcripts to identify meaningful segments of text and apply or refine codes. They then compared their coding to ensure consistency, discussing any discrepancies in how segments were interpreted or categorized. This process helped refine definitions of codes and add new codes that emerged from the data (the inductive aspect, where unanticipated themes can be incorporated). For example, if participants raised a topic not in the initial framework, a new code was created for it. After establishing a common understanding, the remaining five transcripts were coded, with each transcript coded by one of the two researchers. If uncertainty arose about how to classify a particular quote or if a new theme emerged late, those were resolved through discussion or input from a third team member. Through this iterative coding, a final set of themes and subthemes was agreed upon. Then each theme was summarized, noting representative quotes (translated to English for reporting) that exemplified the adolescents' perspectives. The analysis yielded qualitative insights, which were synthesized narratively. Saturation was confirmed by the two researchers that coded the transcriptions.

3.8. Software and Tools

All analyses and data processing made use of established software tools and programming languages.

Environmental exposure data were processed using Geographic Information System (GIS) software. ArcGIS Desktop (versions 10.5 and 10.7.1, Esri Inc., Redlands, CA, USA) was used for tasks such as geocoding addresses, processing satellite images (e.g., calculating NDVI from Landsat bands), and computing network distances to green/blue spaces with the ArcGIS Network Analyst extension. QGIS (version 3.8, open-source) was used for certain spatial data manipulations, such as extracting raster values (NDVI, MODIS vegetation fractions) within specified buffers around each location.

The quantitative data analysis was conducted in the R programming language (R Core Team, Vienna, Austria). R packages employed included: nlme for linear mixed-effects modelling [242]; lme4 for fitting generalized linear models; lavaan for SEM in mediation analysis [243]; mice for multiple imputation [240]; and dagitty to assist in covariate selection via DAG [244]. Data management and plotting were facilitated by tidyverse packages [245].

The WISC-III intelligence test was administered using the standard kit published by Harcourt Assessment, and scoring was done according to the test manual. Spirometry used the MIR MiniSpir devices with the WinSpiro PRO software to record and export lung function data. The GLI-2012 reference values were applied using the published Excel calculator provided by the Global Lung Function Initiative to obtain percent predicted lung function for each child [220].

Focus groups were conducted via the Zoom video-conferencing platform (Zoom Video Communications, San Jose, CA). Each session was recorded (with consent) through Zoom. Audio-video recordings were later securely stored and then transcribed. Transcription was done manually by research staff and checked for accuracy. The transcripts were managed as Microsoft Word documents before being imported into NVivo. NVivo (Release 1.5.2, QSR International) was used for coding and organizing qualitative data.

3.9. Ethical Considerations

All components of this research were conducted with strict adherence to ethical standards for human subjects research. The G21 was initially approved by the Ethics Committee of the University of Porto Medical School / São João Hospital (Porto) on April 27, 2005, and by the Portuguese National Data Protection Authority. The cohort's ethics approval (Ref: CES 02/2005) covered the recruitment and follow-up assessments of participants from birth onwards. In 2017, a renewal approval (Ref: CES-01/2017) was obtained to continue research activities within the cohort as the children grew older, ensuring ongoing compliance with ethical guidelines. All study phases conform to the principles of the Declaration of Helsinki. At each contact, informed consent was obtained: at recruitment and childhood follow-ups, consent was provided by the infants' legal guardians (parents), and as the participants reached adolescence, their assent (and eventually consent once 18) was also obtained.

The focus group study involving adolescents required a separate ethics review. This qualitative study was approved by the Ethics Committee of the Instituto de Saúde Pública da Universidade do Porto (Ref: CE 212/00-2021) prior to recruitment. Parents or legal guardians of selected adolescents were informed about the study's purpose, what participation entailed (group discussions on Zoom), and potential risks/benefits. Written informed consent was obtained from the guardian, and written informed assent was obtained from the adolescents themselves. Participants were reminded that their involvement was voluntary and that they could withdraw at any time or choose not to answer any question that made them uncomfortable.

In conducting focus groups, there was care to create a safe and respectful environment. A researcher moderator and an observer were present. No identifying information was revealed during sessions, and participants were instructed to use first names only and asked to preserve the confidentiality of the discussions they were a part of. The names were later anonymized in transcripts. The audio-video recordings from Zoom were stored in encrypted form on a secure server accessible only to the research team. After transcription, recordings were permanently deleted to prevent any accidental future disclosure of identities. Transcripts were de-identified. Each participant was assigned a

code used in all notes and reports. Quotations presented in the thesis or publications were carefully vetted to ensure they contain no details that could indirectly identify a person.

4. RESULTS

4.1. Residential and school green and blue spaces and intelligence in children: The Generation XXI birth cohort.

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Residential and school green and blue spaces and intelligence in children: The Generation XXI birth cohort



Diogo Queiroz Almeida ^{a,b,*}, Henrique Barros ^{a,c,d}, Ana Isabel Ribeiro ^{a,c,d}

^a EPIUnit - Instituto de Saúde Pública, Universidade do Porto, Rua das Taipas, n° 135, 4050-600 Porto, Portugal

^b Unidade de Saúde Pública, Unidade Local de Saúde de Matosinhos, Rua de Alfredo Cunha 365, 4450-021 Matosinhos, Portugal

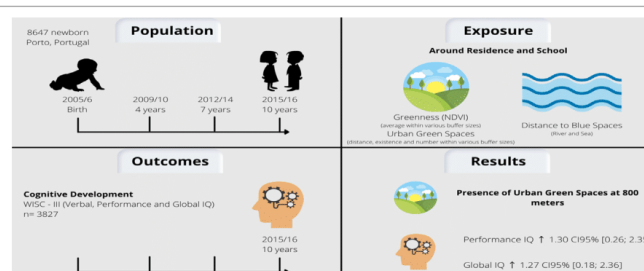
^c Laboratório para a Investigação Integrativa e Translacional em Saúde Populacional (ITR), Rua das Taipas, n° 135, 4050-600 Porto, Portugal

^d Departamento de Ciências da Saúde Pública e Forenses e Educação Médica, Faculdade de Medicina, Universidade do Porto, Alameda Prof. Hernâni Monteiro, 4200-319 Porto, Portugal

HIGHLIGHTS

- Studies on cognition and green space are limited and no study explored blue spaces.
- A large birth cohort and many metrics of green/blue space exposure were used.
- Accessibility to green spaces has a positive association with intelligence.
- This effect was only observed for residential exposures, not school exposures.
- Accessibility to blue spaces is unrelated with intelligence in children.

GRAPHICAL ABSTRACT



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ABSTRACT

Green and blue spaces have numerous health benefits. It has been hypothesized that contact with these spaces can have an important role in cognitive development, because it provides children with unique stimuli that can help develop curiosity, creativity, awareness, and control. This study aimed to estimate the association between exposure to green and blue spaces and the various measures of intelligence quotient (IQ) among children from Porto Metropolitan Area (Portugal).

This investigation used data from the Generation XXI birth cohort. Exposure was assessed by Geographic Information Systems using vegetation indexes and measures of accessibility to urban green spaces and blue spaces in the surroundings of the residence and school, measured at 0, 4, 7 and 10 years. The outcome was the verbal, performance, and global IQ, measured using the Wechsler Intelligence Scale for Children (WISC-III), administered at age 10. Associations were estimated using crude and adjusted multilevel models. The mediation role of air pollution and physical activity was quantified.

This study included 3827 children. The adjusted models showed that having green spaces up to 800 m of the residence was positively associated with performance IQ (1.30 95%CI [0.26; 2.35]) and global IQ (1.27 [0.18; 2.36]). No clear associations were observed regarding accessibility to blue spaces. Physical activity appeared to have a minor mediation role.

Children with urban green spaces around their residences had higher performance and global IQ. Local actors in the sectors of public health and urban planning should promote the creation of green spaces close to residential areas.

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* Corresponding author at: Rua das Taipas, n° 135, 4050-600 Porto, Portugal.

E-mail address: diogo.queiroz.almeida@gmail.com (D.Q. Almeida).

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1. Introduction

Exposure to green spaces (Taylor and Hochuli, 2017) has been associated with better health outcomes, ranging from better physical health (Tamosiunas et al., 2014; Cavaleiro Rufo et al., 2021; Paciência et al., 2021; Li et al., 2008; Witten et al., 2008) and reduced mortality (Gascon et al., 2016) to improved emotional and mental health (Gascon et al., 2015; Britton et al., 2020; Wheeler et al., 2015; White et al., 2013).

Most studies about green and blue spaces have been conducted in adults, but childhood probably represents a critical and sensitive period to this exposure (Kuh et al., 2003). In particular, contact with nature might play an important role in brain development and cognition, as it allows children to explore different situations (e.g. body control and taking risks by interacting with the surroundings, arousing curiosity by the different stimuli) (Frith and Frith, 2011) and promote discovery, creativity and control, which promotes cognitive development (Dadvand et al., 2015; Richardson et al., 2017).

Beneficial effects of green and blue spaces on children's cognition might derive from direct influences such as those above, but can also occur through indirect/mediated pathways: air quality, physical activity, social cohesion, immune tolerance, and stress reduction and attention restoration (Hartig et al., 2014). Exposure to air pollution can lead to oxidative stress, and consequent white matter damage and alternations between the dopamine and glutamate system (Allen et al., 2017). Physical activity has a positive impact in cognitive development by improving oxygen supply to the brain, as well as providing the brain with nutrients, which stimulates the increase of neurohormonal secretion (Bidzan-Bluma and Lipowska, 2018). Green space in the living environment could also lead to more social contacts, which is associated with social cognitive ability (Miller and Peters, 2019). Exposure to natural environments may also improve the microbial input to the immune systems and thus may affect cognitive development (Rook, 2013). Time spent in natural environments may restore a child's attention by reducing mental fatigue that accumulates during the course of the day, as stated by the "Attention Restoration Theory" of Kaplan and Kaplan (1989). This restoration effect is thought to be due to the stimuli present in the environment capturing involuntarily attention and, as such, not interrupting thoughts and reducing mental effort. In addition, according to the "Stress Recovery Theory" by Ulrich (1983), contact with natural spaces is able to reduce psychophysiological responses to stress.

In a pioneer study from 2015, Dadvand et al. observed that cognitive development improved with increasing surrounding school greenness among school-aged children (Dadvand et al., 2015). Later investigations showed a beneficial effect of green space in different measures of brain development, academic performance, and cognition in children considering the exposure to green spaces in the residence (Dadvand et al., 2018) and school (Matsuoka, 2010) surroundings. However, some studies found null associations (Markevych et al., 2019) and even deleterious effects (Browning et al., 2018; Beere and Kingham, 2017) relating cognitive development and green space exposure in residential and school settings.

Despite the growing interest in this field, evidence so far presents a number of limitations that need to be addressed. Firstly, there is lack of evidence regarding the association between blue spaces and cognitive development. Adults living nearer the coastal area have better health overall, and mental health in particular (White et al., 2013), but these findings are not consensual (Triguero-Mas et al., 2015). In children and adolescents, surfing was associated with better mental health (Godfrey et al., 2015). Secondly, most studies used neighbourhood exposures at a single point (Dadvand et al., 2015; Browning et al., 2018; Beere and Kingham, 2017; Bijmens et al., 2020), ignoring the impact of cumulative exposures. Finally, most studies (Dadvand et al., 2015; Browning et al., 2018; Bijmens et al., 2020) measured the amount of vegetation in the child home/school surroundings, but urban green spaces (e.g. parks rather than overall vegetation) may be more beneficial as

they tend to be better equipped and safer, so that caregivers allow children to play in these spaces with less intrusion (Richardson et al., 2017).

Under this background, we hypothesize that the exposure to greenness, to green spaces and to blue spaces may enhance cognition among children. Thus, this study aimed to estimate the association between the exposure to greenness and the accessibility to green and blue spaces in the home and school surroundings with various measures of intelligence quotient (IQ), in children of the Generation XXI birth cohort.

2. Methods

2.1. Study design and participants

This study was conducted in Porto Metropolitan Area, which is a cluster of coastal cities situated in the north-western part of Portugal.

This study uses data from the Generation XXI birth cohort (G21), a population-based birth cohort that recruited 8647 new-borns (wave 1) from five public maternities of the Porto Metropolitan area, between April 2005 and August 2006. Amid all the eligible new-borns, 91.4% of the legal representatives allowed them to participate. The participants were re-evaluated at the ages of four (wave 2, 2009/11, $n = 7459$), seven (wave 3, 2012/14, $n = 6889$) and ten years (wave 4, 2015/17, $n = 6397$). A description of the cohort can be found in previous publications (Alves et al., 2012; Larsen et al., 2013).

G21 was approved by the ethics committee of the Faculdade de Medicina da Universidade do Porto/Hospital de São João and by the National Committee of Data Protection. All the phases of the study complied with the Ethical Principles for Medical Research Involving Human Subjects expressed in the Declaration of Helsinki. Written informed consent was obtained from the legal representatives of the participants in every evaluation.

Children's residential addresses were collected during routine phone calls with the legal representative in each of the four different moments of evaluation. Children's schools were collected from the G21 questionnaires at 7 and 10 years of age. School and residential addresses were processed and georeferenced using ArcGIS Online World Geocoding Service and Google Earth, due to higher positional accuracy (Ribeiro et al., 2014).

Participants were excluded if they studied or resided outside of the Porto Metropolitan Area in any of the four evaluations, or if they were not evaluated for the outcome of interest - the Wechsler Intelligence Scale for Children (WISC III) score (Supplemental material, Appendix A). A total of 3827 children were eligible to be included in this investigation, 2012 male (52.6%) and 1815 female (47.4%).

2.2. Outcome - intelligence

Intelligence was assessed at the age of 10.18 (± 0.18), using the most recently validated Portuguese version of the Wechsler Intelligence Scale for Children - the third edition (WISC III) (Watkins et al., 1997). The WISC III was administered by trained professionals in a controlled environment, taking between 45 and 60 min. The different range of tests that constitute the WISC III provide not only a global Intelligence Quotient (IQ), but also a Verbal IQ and a Performance IQ. The results were standardized (mean of 100 and standard deviation of 15) and compared to a representative sample of peers of the same age.

2.3. Exposure

2.3.1. Greenness

To assess greenness, the Normalized Difference Vegetation Index (NDVI) was used. NDVI is calculated based on the reflection of the electromagnetic waves in the spectrum of visible light and near infrared and can take values between -1 and 1 (with a higher value indicating more greenness). In this study, images with less than 5% of cloudiness from the Landsat 5 and 8 missions from the years of 2005/6, 2009/11, 2012/

14 and 2015/17 (the moments of the G21 evaluations) were used. The greenness surrounding the residence was assessed considering different buffers: 100 m, 250 m and 500 m. The greenness surrounding the schools also included a buffer of 50 m. These distances are in line with previous research (Dadvand et al., 2015). ArcGIS version 10.7.1 was used to process satellite images and QGIS 3.8 was used to extract the mean NDVI in the residence and school surroundings. These calculations were conducted in the scope of EXALAR 21 project (POCI-01-0145-FEDER-030193) and are described elsewhere (Cavaleiro Rufo et al., 2021; Paciência et al., 2021). Because a strong collinearity between NDVI in the different moments of evaluation ($\rho > 0.8$) and no distinct longitudinal trajectories of exposures were identified in latent class models, it was decided to use the mean value of the four moments.

2.3.2. Urban green spaces

All public and free to access urban green spaces (UGS) in the Porto Metropolitan Area ($N = 662$) were included at each evaluation, without restrictions regarding size, location, or any particular characteristic. The cartography was obtained from digital maps provided by the different city halls of Porto Metropolitan Area. Similarly to previous studies (Ribeiro et al., 2019; Hoffmann et al., 2017), the following measures of geographic accessibility to UGS were computed (to the residence and to the school): availability of UGS at 400 m and 800 m, number of available UGS at 400 m and 800 m, minimum distance to the nearest UGS. For fenced UGS, the distance to the nearest entrance was used. For non-fenced UGS, the nearest point was used. ArcGIS version 10.7.1 and the Network Analyst extension were used to calculate the distances to the UGS, employing an updated street network dataset provided by the Environmental Systems Research Institute (ESRI). Again, due to strong collinearity and absence of clear longitudinal trajectories of exposures, the variables were treated as such: the mean value of the distance to the nearest UGS in the four evaluations, the mean number of UGS available in the four evaluations, the existence of UGS in at least three evaluations for the surroundings of the residence (i.e. the majority of the time), and the existence of UGS surrounding the school in both evaluations (7 and 10 years).

2.3.3. Blue spaces

The Portuguese Water Atlas (from the Portuguese "Atlas da Água"), developed by the National Water Resources Information System (SNIRH) under the responsibility of the Portuguese Environment Agency, was used to assess the distance from the children's residence and school to the nearest blue space, including sea and rivers, as previously described (Paciência et al., 2021). The SNIRH was created in 1995 and provides information on hydrometeorological variables and water quality (surface, groundwater and coastal), through the network of water resource monitoring stations in Portugal. ArcGIS version 10.7.1 and the Network Analyst extension were used to calculate the distances. Again, due to strong collinearity and absence of clear longitudinal trajectories, the mean value of the four moments was used.

2.4. Covariates

Analyses were adjusted for the following covariates: sex (male or female); type of school at age 10 (public or private); baseline mother's educational attainment (highest level of education attained and categorized into three different classes: the first including International Standard Classification of Education 2011 (ISCED) 0 to 2 - primary; the second including ISCED 3 - secondary; and the third including ISCED 4 to 6 - tertiary); household monthly income at age 10 (categorized into three classes: less or equal to 1000€, between 1001 and 1500€, and more than 1500€); level of urbanicity at age 10 (determined according to the Portuguese classification of urban areas: predominantly urban areas, moderately urban areas, and predominantly rural areas (Administrative Division [Internet], 2014)); neighbourhood socioeconomic deprivation at age 10 (European Deprivation Index,

described in detail elsewhere (Ribeiro et al., 2018)) (neighbourhood corresponded to the census tract, which in Portugal holds approximately 300 residences); and neighbourhood population density at age 10 (inhabitants per km² (Census [Internet], 2011)). Maternal education, rather than father's education, was used because information on father's educational attainment was missing for 10% of children (vs. 0.2% for maternal education). Additionally, there was a moderate correlation between the two variables ($\rho = 0.6$) (Ribeiro et al., 2020). Plus, maternal education is a widely used indicator of socio-economic position and it is associated with the quality of the neighbourhood of residence and child intelligence (Lawlor et al., 2005; G  n  reux et al., 2008). In addition, maternal education captures material resources and the knowledge-related assets of a person and influences the likelihood of them engaging in health compromising behaviours that may be deleterious to healthy child development (McCrory et al., 2019).

The choice of these variables was theory-driven (Lee, 2014), based on previous literature on the topic (e.g. (Dadvand et al., 2015; Richardson et al., 2017; Markevych et al., 2019)). Socioeconomic factors are important confounders of the association between intelligence (and other outcomes) and green and blue space as disadvantaged individuals tend to have lower access to these environmental resources and lower cognition (Hoffmann et al., 2017; Hackman et al., 2010). In addition, the level of urbanicity influences cognitive development and rural/agricultural areas tend to have lower access to green spaces (Maas et al., 2006; Shammi and Meng, 2021) like parks (Wen et al., 2013; Gouin et al., 2015).

Models were further adjusted for two mediators (Hartig et al., 2014): physical activity (which was assessed by the daily time reported by the participants in physical activity or physical exercise), and air pollution. Outdoor levels of NO₂ (at age 10) were obtained from AirBase - the European air quality database from the European Environment Agency (EEA). EEA provide 1 km grids for NO₂, which were created based on monitoring station data (Agency EE, n.d.).

2.5. Statistical analysis

Generalized mixed models were used to estimate the association between the different exposures of greenness, green spaces and blue spaces and the cognitive development outcome. A hierarchical model was fitted, with neighbourhood and school as random effects. The models were further adjusted to the previously mentioned covariates. Associations were expressed using regression coefficients (beta) and 95% confidence intervals (95%CI). We fitted a total of 69 crude and 69 adjusted models one for each green/blue space exposure variable ($n = 23$) and outcome ($n = 3$). As mentioned, the construction of the models and variable selection was theory-driven. The quality of the model fitting was assessed by using Spearman's correlation coefficients and variance inflation factors (VIFs) to check for potential effects of multicollinearity on model results. The Spearman's correlation matrix between the main exposures and the remaining covariates is shown in Supplemental material, Appendix B.

When statistically significant associations were found, the models were further adjusted for two identified mediators (which were included in the model as covariates): air pollution and physical activity. The percentage of the explanation by each mediator was calculated as $[1 - (\beta_{gm} / \beta_g)] \times 100$, where β_{gm} represents the association factor including the mediator and β_g without it, following Preacher and Kelley method (Preacher and Kelley, 2011) and previous investigations on related topics (Ribeiro et al., 2019).

Effect modification by sex and by indicators of socioeconomic position (mother's educational attainment, type of school, and neighbourhood deprivation) was explored by assessing the statistical significance of multiplicative interactions, using likelihood ratio tests by comparing models with and without interaction terms (Richardson et al., 2017; Putra et al., 2021). The analyses revealed no statistically

significant interaction effects and, thus, results were presented without stratification for indicators of socioeconomic position or sex.

Statistical analysis was performed using R software version 3.6.0 and the statistical package 'lme4' (Bates et al., 2015).

3. Results

3.1. Descriptive statistics

Sample characteristics regarding sex, maternal education, household income, neighbourhood deprivation, population density, level of urbanicity, and type of school, can be found in Table 1.

The mean NDVI in the surroundings of the residences varied between 0.20 and 0.22, depending on the buffer size. Regarding the presence of UGS near the residences, 17.1% of the children had at least one UGS at 400 m, and 41.4% at 800 m. The average number of UGS surrounding the residences ranged between 0 and 4, at 400 m, and between 0 and 9 at 800 m. The minimum distance from the residence to the nearest UGS was 1.09 km, and to the nearest blue space 2.18 km. When separated by type of blue space, it was of 7.56 km for the sea and 2.80 km for the nearest river (Table 2).

The mean NDVI in the surroundings of the school ranged between 0.17 and 0.23. Regarding the presence of UGS near the school, 10.2% of children had at least one UGS within 400 and 35.9% within 800 m. The average number of UGS available in the surroundings of school ranged between 0 and 3 at 400 m, and between 0 and 8.5 at 800 m. The mean distance from school to the nearest green space was 1.13 km and to the nearest blue space was 2.13 km. When separated by type of blue space, it ranged between 7.33 km for the sea and 2.65 km for the nearest river (Table 2).

3.2. Intelligence Quotient according to exposure to green and blue spaces

IQ measures did not significantly differ according to whether the children had UGS at 400 m from their residence. However, children with UGS at 800 m from the residence showed a significantly higher IQ. The number of UGS had a weak positive correlation with the IQ, only statistically significant at 800 m. The distance from the residence to the nearest UGS had a negative correlation with IQ. Overall, the

Table 2

Exposure characteristics of the studied sample (Generation XXI, n = 3827).

NDVI surrounding the residence	100 m	0.20 (0.06) ^a
	250 m	0.22 (0.06) ^a
	500 m	0.20 (0.06) ^a
UGS in the surroundings of the residence	400 m	656 (17.1%) ^b
	800 m	1586 (41.4%) ^b
Number of UGS in the surroundings of the residence	400 m	0 (0–4) ^c
	800 m	0 (0–9) ^c
Distance (km) from the residence	Urban Green Space	1.09 (0.74) ^a
	River	2.80 (2.27) ^a
	Sea	7.56 (4.95) ^a
	Blue space	2.18 (1.46) ^a
	50 m	0.17 (0.04) ^a
NDVI surrounding the school	100 m	0.19 (0.04) ^a
	250 m	0.22 (0.05) ^a
	500 m	0.23 (0.05) ^a
UGS in the surroundings of the school	400 m	391 (10.2%) ^b
	800 m	1373 (35.9%) ^b
Number of UGS in the surroundings of the school	400 m	0 (0–3) ^c
	800 m	0.5 (0–8.5) ^c
Distance (km) from the school	Urban Green Space	1.13 (4.50) ^a
	River	2.65 (2.22) ^a
	Sea	7.33 (5.52) ^a
	Blue space	2.13 (1.41) ^a
	50 m	0.17 (0.04) ^a

Normalized Difference Vegetation Index (NDVI); Urban Green Space (UGS).

^a Mean (standard deviation).

^b Number (percentage).

^c Median (range).

NDVI in the surroundings of the residence had a weak, negative correlation with most measures of IQ. The distance from the residence to the sea had a negative correlation with IQ (but not from the school). The distance to the nearest river or any type of blue space was not correlated with IQ (Supplemental material, Appendices C and D).

In terms of school surroundings, children with a UGS within a radius of 400 and 800 m had a higher IQ for most measures. The number of UGS at 400 m and 800 m had a weak and positive correlation with the IQ. The distance to the nearest UGS had a weak and positive correlation with the IQ. The correlations with blue spaces were non-significant and showed no clear direction. The NDVI in the school surroundings showed a weak and negative correlation with the IQ at 10 years of age (Supplemental material, Appendices C and D).

3.3. Unadjusted and adjusted associations between green spaces, blue spaces and IQ

The presence of a UGS within 800 m from the residence was positively associated with all measures of IQ in the unadjusted models and, in the adjusted models, it was associated with the performance IQ (1.30 95%CI [0.26; 2.35]), and global IQ (1.27 [0.18; 2.36]) (Table 3). After adjusting for the two studied mediators, pollution (NO₂) and physical activity, the associations remained unchanged, and no meaningful mediation effect was identified (2.1% for physical activity for performance IQ, Supplemental material, Appendix E). For a distance of 400 m from the residence, there was no association between the existence of UGS and any measure of IQ.

The number of UGS available at 400 m from the residence was not associated with the different IQ measures. For a distance of 800 m, there was a positive association in the unadjusted model, but not in the adjusted model. The distance to the nearest UGS had a negative association with the IQ in the crude model, but the effect disappeared after adjustment. The distance from the residence to the nearest river, as well as to the nearest blue space (sea or river), showed no clear association with the IQ. The shortest distance from the residence to the sea showed a negative statistically significant association in the unadjusted model, but not in the adjusted. The NDVI in the surroundings of the residence

Table 1
Characteristics of the studied sample at baseline (Generation XXI, n = 3827).

	Mean (standard deviation) or absolute frequency (relative frequency)
Sex (male)	2012 (52.6%)
Maternal education (at baseline)	
Primary	1805 (47.2%)
Secondary	886 (23.2%)
Tertiary	1136 (29.7%)
Household income	
≤1000 euros	1097 (32.2%)
1001–1500 euros	1044 (30.6%)
>1500 euros	1266 (37.2%)
Level of urbanicity of the neighbourhood of the residence	
Predominantly urban	3705 (96.8%)
Moderately urban	97 (2.5%)
Predominantly rural	25 (0.7%)
Socioeconomic deprivation index of the neighbourhood of the residence	−0.18 (2.53)
Population density of the neighbourhood of the residence	9431 (9241)
Type of school (private school)	402 (10.5%)
Socioeconomic deprivation index of the neighbourhood of the school	−0.54 (2.66)
Population density of the neighbourhood of the school	3071 (3408)

Table 3
Unadjusted and adjusted associations (beta and 95% confidence interval) between the different measures of exposure to green spaces and the IQ (Generation XXI, $n = 3827$).

		Verbal IQ	Performance IQ	Global IQ
UGS in the surroundings of the residence	400 m	1.10 (−0.52; 2.72)	1.65 (0.18; 3.12)	1.64 (0.04; 3.25)
	400 m adjusted ^a	−0.12 (−1.69; 1.47)	0.48 (−1.05; 1.20)	0.25 (−1.34; 1.83)
	800 m	1.74 (0.62; 2.85)	1.85 (0.85; 2.85)	2.13 (1.04; 3.23)
	800 m adjusted ^a	0.81 (−0.27; 1.90)	1.30 (0.26; 2.35)	1.27 (0.18; 2.36)
Number of UGS in the surroundings of the residence	400 m	0.41 (−0.67; 1.49)	0.66 (−0.31; 1.63)	0.66 (−0.41; 1.72)
	400 m adjusted ^a	−0.27 (−1.32; 0.78)	0.01 (−1.00; 1.02)	−0.14 (−1.19; 0.92)
	800 m	0.49 (0.07; 0.90)	0.42 (0.05; 0.79)	0.54 (0.14; 0.95)
	800 m adjusted ^a	0.11 (−0.30; 0.51)	0.25 (−0.13; 0.64)	0.22 (−0.18; 0.62)
Distance from the residence to the nearest UGS (km)	UGS distance	−1.33 (−2.06; −0.60)	−0.91 (−1.56; −0.27)	−1.33 (−2.04; −0.61)
	UGS distance adjusted ^a	−0.62 (−1.35; 0.11)	−0.55 (−1.25; 0.15)	−0.70 (−1.43; 0.03)
NDVI surrounding the residence	100 m	−14.55 (−23.02; −6.07)	−6.55 (−14.17; 1.07)	−12.50 (−20.85; −4.14)
	100 m adjusted ^a	−5.35 (−14.62; 3.91)	−0.84 (−9.74; 8.07)	−3.53 (−12.81; 5.74)
	250 m	−14.40 (−22.93; −5.87)	−8.08 (−15.72; −0.44)	−13.40 (−21.79; −5.00)
	250 m adjusted ^a	−4.61 (−13.90; 4.68)	−2.19 (−11.11; 6.73)	−3.99 (−13.28; 5.30)
	500 m	−13.10 (−22.04; −4.15)	−5.58 (−13.62; 2.47)	−10.92 (−19.74; −2.09)
UGS in the surroundings of the school	500 m adjusted ^a	−5.24 (−15.15; 4.67)	−2.03 (−11.56; 7.51)	−3.92 (−13.85; 6.01)
	400 m	1.62 (−0.20; 3.43)	0.92 (−0.75; 2.58)	1.50 (−0.31; 3.31)
	400 m adjusted ^a	0.49 (−1.12; 2.09)	−0.16 (−1.67; 1.36)	0.27 (−0.13; 1.88)
	800 m	2.25 (1.00; 3.51)	1.17 (0.05; 2.29)	2.00 (0.75; 3.26)
	800 m adjusted ^a	0.83 (−0.53; 2.20)	0.55 (−0.71; 1.83)	0.83 (−0.54; 2.19)
Number of UGS in the surroundings of the school	400 m	2.01 (0.81; 3.21)	0.84 (−0.24; 1.92)	1.69 (0.49; 2.89)
	400 m adjusted ^a	0.69 (−0.41; 1.79)	0.19 (−0.84; 1.22)	0.53 (−0.57; 1.63)
	800 m	0.81 (0.35; 1.28)	0.23 (−0.18; 0.64)	0.59 (0.12; 1.05)
	800 m adjusted ^a	0.19 (−0.22; 0.60)	−0.03 (−0.40; 0.36)	0.08 (−0.33; 0.49)
	UGS beta	0.03 (−0.08; 0.15)	0.07 (−0.03; 0.18)	0.07 (−0.05; 0.18)
Distance from the school to the nearest UGS (km)	UGS beta adjusted ^a	0.05 (−0.06; 0.16)	0.05 (−0.05; 0.16)	0.06 (−0.05; 0.17)
	NDVI surrounding the school			
NDVI surrounding the school	50 m	−28.78 (−13.67; −13.89)	−20.74 (−33.56; −7.90)	−27.58 (−42.33; −12.83)
	50 m adjusted ^a	−8.95 (−22.32; 4.52)	−12.70 (−25.03; −0.48)	−11.64 (−24.96; 1.69)
	100 m	−31.61 (−46.64; −16.58)	−20.09 (−33.00; −7.14)	−29.37 (−44.27; −14.46)
	100 m adjusted ^a	−16.52 (−30.33; −2.60)	−12.99 (−25.72; −0.40)	−16.59 (−30.33; −2.84)
	250 m	−25.76 (−39.62; −11.91)	−10.73 (−22.46; 1.03)	−21.30 (−35.04; −7.53)
	250 m adjusted ^a	−11.96 (−24.68; 0.79)	−3.81 (−15.63; 7.82)	−8.84 (−21.55; 3.82)
	500 m	−20.64 (−34.64; −6.62)	−8.05 (−19.88; 3.86)	−16.18 (−30.08; −2.24)
	500 m adjusted ^a	−5.13 (−18.26; 7.99)	−1.74 (−14.13; 10.34)	−3.11 (−16.30; 9.96)

Adjusted for sex, maternal education, monthly household income, population density, neighbourhood socioeconomic deprivation index, level of urbanicity and type of school, bold denotes statistically significant results.

Normalized Difference Vegetation Index (NDVI); Urban Green Space (UGS).

^a $p < 0.05$.

had a negative and statistically significant association with the IQ in the unadjusted model (not in the adjusted) (Tables 3 and 4).

There were no associations between the existence of UGS at 400 m from the school and the IQ. For a distance of 800 m, there was a positive association with all IQ measurements. However, after adjustment, the associations disappeared. The number of UGS available at 400 m and 800 m had a positive association with the verbal and global IQ in the unadjusted model only. The distance from school to the nearest UGS, sea, river, or blue space had no association with the IQ. The NDVI in the surroundings of the school had a negative and statistically significant association for all buffers assessed, in the crude model. In the adjusted

model, the association remained for a distance of 50 m and performance IQ (−12.70 95%CI [−25.03; −0.48]) and for a distance of 100 m and verbal (−16.52 [−30.33; −2.60]), performance (−12.99 [−25.72; −0.40]) and global IQ (−16.59 [−30.33; −2.84]).

The analyses revealed no statistically significant interaction effects of socioeconomic position or gender ($p > 0.1$).

4. Discussion

The aim of this study was to assess the influence of the exposure to nature, in the cognitive development of children. It was observed that

Table 4
Unadjusted and adjusted associations (beta and 95% confidence interval) between the different measures of exposure to blue spaces and the IQ (Generation XXI, $n = 3827$).

		Verbal IQ	Performance IQ	Global IQ
Distance from the residence to the river (km)	Unadjusted	0.16 (−0.07; 0.40)	0.11 (−0.11; 0.32)	0.16 (−0.08; 0.39)
	Adjusted ^a	0.11 (−0.11; 0.34)	0.09 (−0.13; 0.31)	0.12 (−0.11; 0.35)
Distance from the residence to the sea (km)	Unadjusted	−0.13 (−0.24; −0.02)	−0.11 (−0.20; −0.01)	−0.14 (−0.24; −0.03)
	Adjusted ^a	−0.01 (−0.12; 0.10)	−0.06 (−0.16; 0.05)	−0.03 (−0.14; 0.08)
Distance from the residence to the nearest blue space (km)	Unadjusted	−0.051 (−0.42; 0.32)	0.07 (−0.26; 0.40)	0.01 (−0.35; 0.38)
	Adjusted ^a	0.09 (−0.26; 0.44)	0.15 (−0.19; 0.49)	0.14 (−0.21; 0.49)
Distance from the school to the river (km)	Unadjusted	0.13 (−0.19; 0.45)	0.19 (−0.08; 0.46)	0.20 (−0.12; 0.52)
	Adjusted ^a	0.16 (−0.11; 0.43)	0.17 (−0.07; 0.41)	0.20 (−0.07; 0.47)
Distance from the school to the sea (km)	Unadjusted	−0.04 (−0.16; 0.08)	−0.05 (−0.16; 0.05)	−0.05 (−0.17; 0.07)
	Adjusted ^a	0.04 (−0.07; 0.14)	−0.04 (−0.13; 0.06)	0.00 (−0.10; 0.11)
Distance from the school to the nearest blue space (km)	Unadjusted	−0.10 (−0.58; 0.37)	−0.03 (−0.38; 0.43)	−0.04 (−0.51; 0.44)
	Adjusted ^a	0.05 (−0.36; 0.46)	0.02 (−0.36; 0.39)	0.04 (−0.37; 0.45)

Adjusted for sex, maternal education, monthly household income, population density, neighbourhood socioeconomic deprivation index, level of urbanicity and type of school, bold denotes statistically significant results.

^a $p < 0.05$.

children with UGS in the surroundings of the residence had a higher performance IQ and global IQ at age 10, but no association was found when considering the same exposure in the school surroundings. Contrastingly, greenness (NDVI) in the immediate surroundings of school was negatively associated with IQ, but no association was found when looking at greenness around the residential locations. Regarding blue spaces, regardless the setting – residence or school –, no clear associations were observed between the proximity to these natural spaces and IQ.

The positive effect of the existence of UGS in the surrounding of the residence is in line with the published evidence (Dadvand et al., 2015, 2018; Matsuoka, 2010). However, the effect size observed was relatively small: after the adjustment for all the considered covariates, we may expect that an average child benefitting from at least an urban green space in a radius of 800 m around his residence should have a 1.30% higher value of performance IQ and a 1.27% higher value of global IQ, than a child which have no urban green space at all in his residence surroundings. Nevertheless, an increase of 1% in the global IQ of the population can increase the economic growth of a country by a value between 2.46% and 3.80% (Burhan et al., 2014). Our findings find echo on evidence from experimental studies about the therapeutic effects of nature. For instance, authors have shown interacting with nature or viewing pictures of nature could expand certain cognitive functions in adults (Berman et al., 2008) and improve concentration and attention in children (Faber Taylor and Kuo, 2009). There are a few mechanisms that can explain the beneficial effects of nature, in particular green space, in cognitive development – air pollution, physical activity, socialization, attention restoration and stress reduction – which are fully detailed in the Introduction section of this manuscript. In this study, physical activity showed a small mediating role in the effect of the distance to the nearest UGS, in an order of magnitude close to what was previously described (Ribeiro et al., 2019). However, no mediation effect of air pollution was identified, which can be related with the fact that the measure of air pollution, NO₂, lacks spatial resolution (as discussed in the limitations section of this discussion).

No effect was observed for the NDVI in the surroundings of the residence, which is also in line with previous investigation (Dadvand et al., 2015); this may be due to the NDVI being a worse measure of green space exposure than UGS (Kahn, 1997). Similarly, the existence of UGS surrounding the schools did not have an influence on cognitive development (in line with 64% of the studies reviewed (Browning and Rigolon, 2019)). In opposition to one of the hypotheses, the NDVI in the close surrounding (50 to 100 m) of the schools showed a negative association with the cognitive development. These results can be due to uncontrolled socioeconomic factors (Beere and Kingham, 2017), and can also be related to the fact that schools located in poorer areas have more wild vegetation in their surroundings (Browning et al., 2018).

Regarding blue spaces, no clear effect was observed, considering either the residence as the setting or the school. It is possible that the beneficial effect of blue spaces is only relevant for very small distances (or at least smaller than the majority of the children studied). In fact, Amoly and colleagues, using the reported number of days spent on the beach, found that blue spaces had in fact a positive effect on cognitive development of schoolchildren (Amoly et al., 2014). However, such variable was not collected within the G21 cohort.

With the current migration patterns, it is expected that 60% of people will live in urban areas by 2030 (UNFPA, 2007). As such, it is important to mitigate the negative effects that can arise from this shift. This study shows that, one way to promote cognitive development of children, is by creating UGS. The effect was more evident for UGS in the surroundings of the residential environments. This can translate into practical policies to be thought out by policymakers when thinking about urban planning, for example by increasing the number of UGS. In the short-term, the cognitive development of children would increase and, in the long term, lasting effects could still be found in the social and mental health of the adults.

The present investigation has both its merits and flaws. Starting by the merits, it assesses the importance of exposure in various moments in time, starting at birth. It uses different measures of exposure to green spaces, including not only vegetation but also measures of proximity to UGS, which are still infrequently used in this research field, but might be better indicators of green space exposure (Fan et al., 2011). It is the first to assess the association between the exposure to blue spaces and cognitive development in children. It includes sensitivity analyses to assess the impact of the use of different buffer sizes. And it adjusts for the most commonly identified confounders in the literature (Dadvand et al., 2015; Ribeiro et al., 2019; Madzia et al., 2019; Mueller and Flouri, 2020).

However, some limitations need to be discussed. The first one is the “Uncertain Geographic Context Problem” (Kwan, 2012), which arises when the contextual area does not reflect the true area to which the person is actually exposed; although this problem may be less pronounced than in adult populations (which have more mobility and autonomy), children may also visit and stay in locations other than the residence and school. Additionally, availability and geographical accessibility to green and blue spaces were measured as proxies of utilization. Proximity is a key determinant of public space utilization (Schipperijn et al., 2013) but other individual (e.g. preferences, health status) and ecological (e.g. quality of spaces) determinants may be implicated and, thus, availability and geographical accessibility may not be good proxies. Also, in terms of exposure, the fact that only quantity and not quality of spaces is assessed is also a limitation, since different types/features of spaces can have different health impacts (Wheeler et al., 2015). Additionally, the images used to assess the NDVI have a minimum resolution of 30 m by 30 m. Smaller gardens may not be detected. Another problem relates to the relatively low resolution of the variable used to estimate the mediation effect of air pollution (NO₂ in raster cells of 1 km by 1 km), which may have limited the assessment of pollution as a mediator at a local scale. Regarding physical activity, available data did not differentiate between indoor and outdoor activities, which makes the study of this mediator less precise. Concerning other possible mediators, stress and social contacts were not measured, and as such, their possible role was not accounted. As with other longitudinal studies, the loss to follow-up can introduce a selection bias if the dropout is not random. Participants that were included in this study had higher maternal education ($p < 0.001$), household income ($p < 0.001$) and lived in less deprived neighbourhoods according to the socioeconomic deprivation index ($p < 0.001$), but had similar population density ($p = 0.121$). This may weaken the external validity of the study and the capacity to extrapolate the results to individuals of lower socioeconomic position. Establishing causation is challenging and extremely complex in studies about the relationship between nature and health (Lee and Maheswaran, 2011), as associations may be affected by neighbourhood self-selection bias or residual confounding. However, various strong points, aligned with the criteria those proposed by Austin Bradford-Hill, reinforce this work and the likelihood that the associations identified are causal: 1) the fact that there is already previous evidence in similar areas (consistency); 2) the fact that there is biological plausibility backing up the relationship between cognition and nature (plausibility) and 3) the fact that, even after adjustment for well-known confounders, the associations remained with similar strength (strength).

5. Conclusion

In conclusion, this study showed that the existence of UGS in the surroundings of the residence of children had a positive effect on the cognitive development at 10 years of age. The effect of blue spaces and the effect of greenness and UGS in the surroundings of schools were not evident. This investigation brings about new evidence to the growing body of evidence concerning the health benefits of greenness and UGS, which can be translated into urban planning practices.

CRediT authorship contribution statement

Diogo Queiroz Almeida: Conceptualization, Formal analysis, Data curation, Writing – original draft. **Henrique Barros:** Project administration, Supervision, Writing – review & editing. **Ana Isabel Ribeiro:** Conceptualization, Data curation, Supervision, Writing – review & editing.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.scitotenv.2021.151859>.

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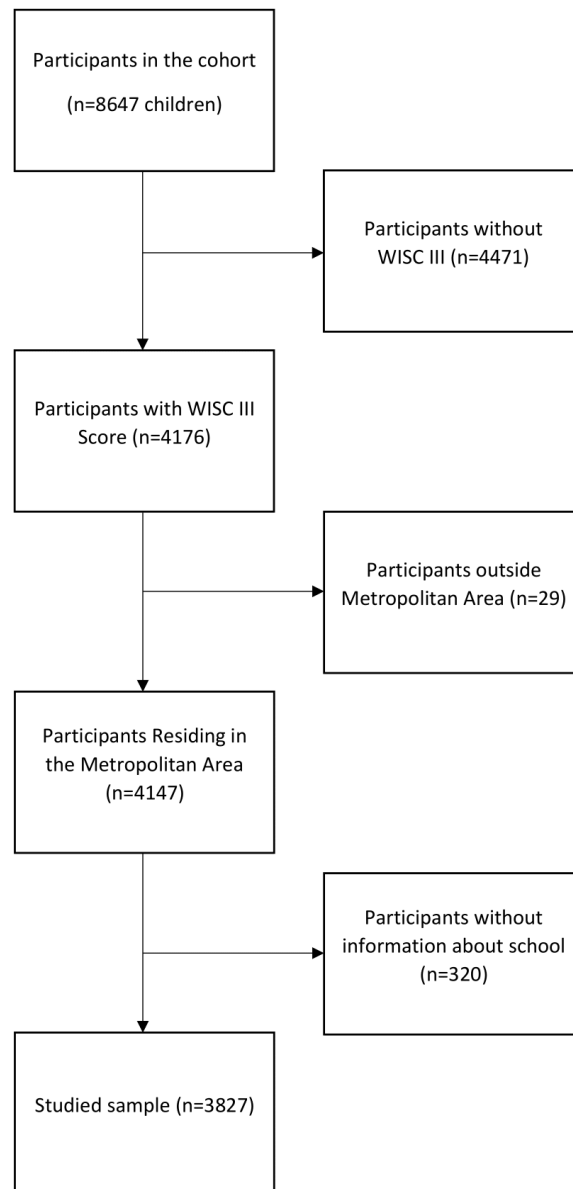
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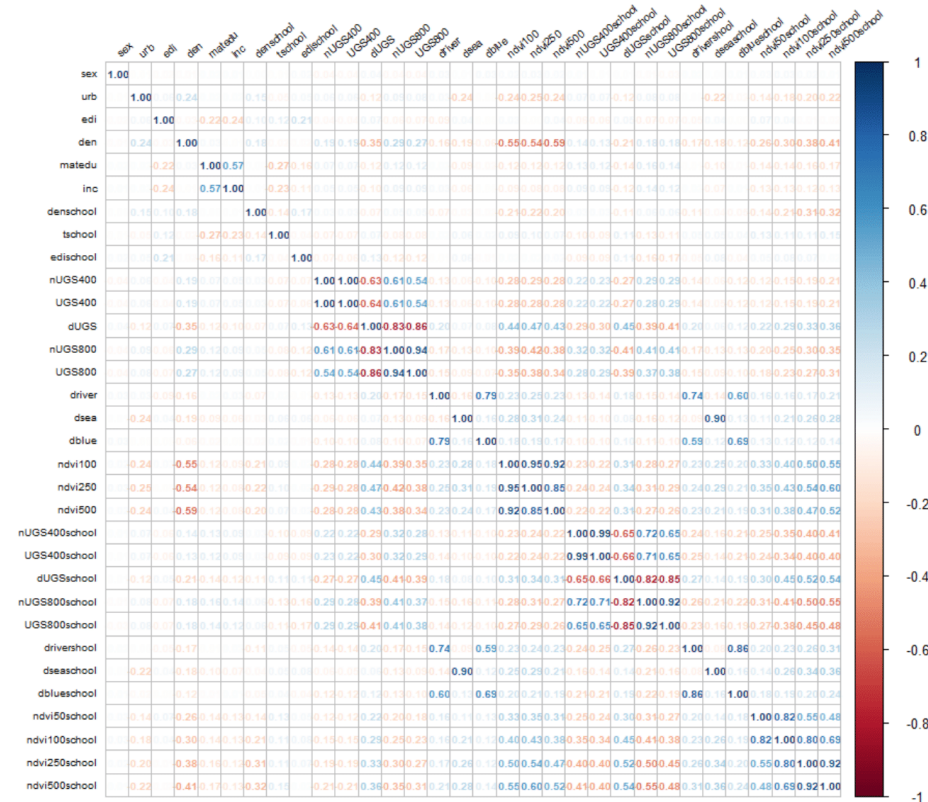
Supplemental Material

Appendix A



Appendix B

Spearman correlation between different exposures



sex – sex

urb – level of urbanicity

edi – neighbourhood socioeconomic deprivation surrounding the residence

den – neighbourhood population density surrounding the residence

matedu – mother's education attainment

inc – household monthly income

denschool – neighbourhood population density surrounding the school

tschool – type of school

edischool – neighbourhood socioeconomic deprivation surrounding the school

nUGS400 – Number of UGS in the surroundings of the residence at 400 meters

UGS400 – Presence of UGS in the surroundings of the residence at 400 meters

dUGS – Distance from the residence to the nearest UGS (km)

nUGS800 – Number of UGS in the surroundings of the residence at 800 meters

UGS800 – Presence of UGS in the surroundings of the residence at 800 meters

driver – Distance from the residence to the river (km)

dsea – Distance from the residence to the sea (km)

dblue – Distance from the residence to the nearest blue space (km)

ndvi100 – NDVI surrounding the residence at 100 meters

ndvi250 – NDVI surrounding the residence at 250 meters

ndvi500 – NDVI surrounding the residence at 500 meters

nUGS400school – Number of UGS in the surroundings of the school at 400 meters

UGS400school – Presence of UGS in the surroundings of the school at 400 meters

dUGSschool – Distance from the school to the nearest UGS (km)

nUGS800school – Number of UGS in the surroundings of the school at 800 meters

UGS800school – Presence of UGS in the surroundings of the school at 800 meters

driverschool – Distance from the school to the river (km)

dseaschool – Distance from the school to the sea (km)

dblueschool – Distance from the school to the nearest blue space (km)

ndvi50school – NDVI surrounding the school at 50 meters

ndvi100school – NDVI surrounding the school at 100 meters

ndvi250school – NDVI surrounding the school at 250 meters

ndvi500school – NDVI surrounding the school at 500 meters

Appendix C

Intelligence Quotient (IQ) according to the different measures of exposure to green spaces (Generation

XXI, n=3827)

		Verbal IQ	Performance IQ	Global IQ
IQ according to the presence of UGS in the surroundings of the residence	400 meters (yes)	103.42	97.66	99.96
	400 meters (no)	102.40	96.53	98.70
	p value	0.156	0.076	0.067
	800 meters (yes)	103.65	97.85	100.25
	800 meters (no)	101.79	95.91	97.95
	p value	0.001	<0.001	<0.001
Correlation between the IQ and the	Number of UGS at 400 meters	0.016 (0.327)	0.022 (0.179)	0.022 (0.183)
	Number of UGS at 800 meters	0.041 (0.011)	0.037 (0.023)	0.045 (0.005)
	Shortest distance to the nearest UGS	-0.061 (<0.001)	-0.046 (0.005)	-0.062 (<0.001)
Correlation between IQ, and the NDVI surrounding the residence	100 meters	-0.061 (<0.001)	-0.028 (0.083)	-0.052 (0.001)
	250 meters	-0.059 (<0.001)	-0.034 (0.035)	-0.054 (0.001)
	500 meters	-0.053 (0.001)	-0.023 (0.157)	-0.044 (0.007)
IQ according to the presence of UGS in the surroundings of the school	400 meters (yes)	104.32	97.72	100.54
	400 meters (no)	102.37	96.60	98.72
	p value	0.021	0.156	0.032
	800 meters yes	104.29	97.73	100.57
	800 meters no	101.60	96.14	97.67
	p value	<0.001	0.002	<0.001
Correlation between the IQ and the	Number of UGS at 400 meters	0.070 (<0.001)	0.040 (0.014)	0.064 (<0.001)
	Number of UGS at 800 meters	0.080 (<0.001)	0.039 (0.015)	0.070 (<0.001)
	Shortest distance to the nearest UGS	0.002 (0.928)	0.014 (0.394)	0.008 (0.613)

Correlation between IQ and the NDVI surrounding the school	50m	-0.077 (<0.001)	-0.070 (<0.001)	-0.083 (<0.001)
	100m	-0.085 (<0.001)	-0.069 (<0.001)	-0.088 (<0.001)
	250m	-0.081 (<0.001)	-0.047 (0.004)	-0.075 (<0.001)
	500m	-0.071 (<0.001)	-0.045 (0.006)	-0.068 (<0.001)

*correlation coefficient (p-value), bold denotes statistically significant results

Normalized Difference Vegetation Index (NDVI); Urban Green Space (UGS)

Appendix D

Correlation (Pearson) between the Intelligence Quotient (IQ) and the different measures of exposure to blue spaces (Generation XXI, n=3827)

		Verbal IQ	Performance IQ	Global IQ
Distance (km) from the residence	River	0.022 (0.170)	0.016 (0.326)	0.022 (0.180)
	Sea	-0.035 (0.030)	-0.033 (0.039)	-0.039 (0.017)
	Blue space	-0.004 (0.823)	0.007 (0.667)	0.002 (0.918)
Distance (km) from the school	River	0.014 (0.384)	0.020 (0.228)	0.019 (0.248)
	Sea	-0.019 (0.237)	-0.030 (0.069)	-0.028 (0.090)
	Blue space	-0.002 (0.889)	0.000 (0.996)	-0.001 (0.945)

^a correlation coefficient (p-value), bold denotes statistically significant results

Appendix E

Mediation analysis for positive adjusted associations (beta and 95% confidence interval) and percentage explanation when association weakens after taking mediation into account

		<i>Main analysis</i>	<i>Adjusted for physical activity</i>	<i>Adjusted pollution</i>	<i>Explanation by physical activity</i>	<i>Explanation by pollution</i>
<i>Presence of UGS in the surroundings of the residence at 800 meters</i>	Performance IQ	1.30 (0.26; 2.35)	1.28 (0.22; 2.34)	1.32 (0.24; 2.41)	2.1%	None
	Global IQ	1.27 (0.18; 2.36)	1.44 (0.42; 2.46)	1.54 (0.50; 2.58)	None	None

bold denotes statistically significant results

4.2. Green and blue spaces and lung function in the Generation XXI cohort: a life course approach.

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Green and blue spaces and lung function in the Generation XXI cohort: a life-course approach

Diogo Queiroz Almeida ^{1,2,3,4,9}, Inês Paciência ^{1,2,9}, Carla Moreira⁵, João Cavaleiro Rufo ^{1,2},
André Moreira^{1,2,6,7,8}, Ana Cristina Santos ^{1,2,6}, Henrique Barros ^{1,2,6} and Ana Isabel Ribeiro^{1,2,6}

¹EPIUnit – Instituto de Saúde Pública, Universidade do Porto, Porto, Portugal. ²Laboratório para a Investigação Integrativa e Translacional em Saúde Populacional (ITR), Porto, Portugal. ³Departamento de Ciências da Saúde Pública e Forenses e Educação Médica, Faculdade de Medicina, Universidade do Porto, Porto, Portugal. ⁴Unidade de Saúde Pública, Unidade Local de Saúde de Matosinhos, Matosinhos, Portugal. ⁵Cmat – Centre of Mathematics School of Sciences, University of Minho, Braga, Portugal. ⁶Faculdade de Medicina da Universidade do Porto, Porto, Portugal. ⁷Serviço de Imunoalergologia, Centro Hospitalar Universitário de São João, Porto, Portugal. ⁸Faculdade de Ciências da Nutrição e Alimentação da Universidade do Porto, Porto, Portugal. ⁹Equal contributors.

Corresponding author: Diogo Queiroz Almeida (diogo.queiroz.almeida@gmail.com)



Shareable abstract (@ERSpublications)

More people are living in urban areas lacking natural spaces, which can have deleterious health effects. Children who increased their exposure to greenness had better lung function. Making cities greener may lead to respiratory health improvements. <https://bit.ly/39ZGG4c>

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Abstract

Background Exposure to natural environments may affect respiratory health. This study examined the association of exposure to green and blue spaces with lung function in children, and assessed the mediation effect of air pollution and physical activity.

Methods The study used data from the Generation XXI, a population-based birth cohort from the Porto Metropolitan Area (Portugal). Residential Normalised Difference Vegetation Index (NDVI) at different buffers (100, 250 and 500 m), the accessibility to urban green spaces (UGS) within 400 and 800 m and the minimum distance to the nearest UGS and to the nearest blue spaces were assessed at birth, 4, 7 and 10 years of age. Three life-course measures were calculated: averaged exposure, early-life exposure (birth) and exposure trend over time (change in exposure). Forced vital capacity (FVC), forced expiratory volume in 1 s (FEV₁) and forced expiratory flow between 25% and 75% of FVC (FEF_{25–75%}) at 10 years were used as outcomes. To assess associations, linear regression models and path analysis were used.

Results This study included 3278 children. The adjusted models showed that increasing the NDVI exposure over time within 100 m of the child's residence was associated with higher values of FEV₁ (L) and FEF_{25–75%} (L·s⁻¹) (β 0.01, 95% CI 0.0002–0.03 and β 0.02, 95% CI 0.001–0.05, respectively). No significant associations were observed for the remaining measures of exposure, and no mediation effect was found for pollution or physical activity.

Conclusion Increasing exposure to greenness at close proximity from residences was associated with improved lung function. While the mechanism remains unknown, this study brings evidence that city greening may improve children's respiratory health.

Introduction

Exposure to natural environments is associated with better health outcomes [1], but green (*i.e.* vegetated land [2]) and blue space (visible surface water [3]) studies tend to focus on adults. However, childhood may be sensitive to such exposures [4]. Longitudinal studies have shown that decrements of lung function established in the first few years after birth track to adulthood, which indicates that early childhood is a sensitive period in lung function development [5, 6]. Additionally, lung function deficits that have been tracked from childhood into adulthood have been associated with a higher prevalence of respiratory diseases and premature death [7]. Although lung function catch-up might happen, this phenomenon is still

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not certain [8]. Lung function is an important indicator of child growth, with children with accelerated body mass index gain showing a higher predicted forced vital capacity (FVC) and lower forced expiratory volume in 1 s (FEV_1)/FVC ratio [9]. These indicators are used to assess lung function, with decreased values of FEV_1 and FVC being associated with airway obstruction and lung restriction, respectively [10]. Two of the main airway obstruction diagnoses are asthma and COPD, with childhood asthma being associated with COPD development later in life [11]. Since the lung function development is a continuum, is crucial to identify the environmental factors that affect lung function in childhood, so that it is possible to intervene early and decrease the risk of respiratory diseases in later life [7].

Exposure to nature might influence lung function through different mediators, namely physical activity and air pollution [12, 13]. Green [12] and blue [1] spaces may promote increased levels of physical activity, which can improve both FEV_1 and FVC [14], possibly by the stretch of the airway smooth muscle, leading to a reduced bronchoconstriction [15]. In addition, the presence of green [13] and blue [1] spaces may improve air quality, by filtering air pollutants and/or mitigating the pollution levels. Air pollution is commonly higher in areas with lower amounts of natural spaces, which may lead to chronic inflammation and, consequently, increases in reactivity, smooth-muscle contraction and secretions [16].

The association between green spaces and different measures of respiratory health in children [17–27] and adults [28] has been evaluated, but several evidence gaps remain. Most studies have measured the development of disease, such as asthma (either by questionnaires [18, 19, 22–24], or medication [17]) and only four studies have measured lung function [25–29]. Regarding these four studies, one suggested that children living in more vegetated places or in close proximity of green spaces across their life-course have better lung function [29]; two reported no association between greenness and the respiratory system resistance and respiratory system reactance [25] and spirometry measures [27]; while the other found no effect modification of greenness in the association between pollens and the fractional exhaled nitric oxide [26]. Furthermore, the previous studies assessed the effect of greenness at different moments and using different approaches. Three of the studies used a cross-sectional analysis, evaluating the effect among children [25–27] and one longitudinal study assessed the effect of exposure to residential green spaces across life-course and lung function up to the age of 24 years [29].

Most studies only used greenness measures [20, 22, 24], but it has been described that accessibility to urban green spaces (UGS) can be better proxies of green space exposure [30]. In addition, to our knowledge, accessibility to blue spaces has seldom been explored as a potential determinant of lung function [27], although there is a beneficial effect of aerosolised water in asthma in children [31]. Finally, there is a lack of work incorporating a life-course perspective [32]. Exposures can build up over time and influence health later and people can change residences, and thereby the surrounding natural environment. Furthermore, there are certain time windows (sensitive periods) in which environmental exposures can have a bigger impact, namely the perinatal period [33].

So, under this background, we hypothesise that greenness and geographical accessibility to green and blue spaces have a positive impact on children's lung function. Therefore, we aimed at estimating the association between the longitudinal exposure to greenness and geographical accessibility to green and blue spaces from birth to 10 years of age and the lung function of children at the age of 10 years, using data from the Generation XXI (G21) birth cohort. Furthermore, we aimed to assess the mediation effect of air pollution and physical activity in the studied associations.

Methods

Study participants

The study used data from the G21, which includes 8495 mothers and 8647 newborns delivered in 2005 and 2006 in the Porto Metropolitan Area in Northern Portugal (www.geracao21.com/en/). The initial recruitment took place between April 2005 and September 2006 at all public maternity units, where 95% of the region's births occur. All participants were invited to be re-evaluated at four (2009/2011), seven (2012/2014) and 10 (2015/2017) years of age [34]. At ages 4, 7 and 10 years, 7459, 6889 and 6392 children participated (86%, 80% and 74% of the initial cohort), respectively (supplementary figure S1) [35]. Ethical approval for the study was obtained from the ethics committee of the University Hospital Center of São João (Porto, Portugal; CES-01/2017) and signed informed consent was obtained from all participants' legal representatives.

Each child's residential address was collected during routine telephone calls with the caregiver. If the child changed residence from birth to 10 years of age, the new address was used to estimate the exposure at the time of evaluation. For the present study, the subsample of children living in Porto Metropolitan Area

since birth to data collection and with data on lung function parameters at 10 years of age was included, totalling 3278 children.

Health outcomes

Lung function was measured by spirometry at 10 years of age using a portable spirometer (MIR Minispir) by trained technicians, according to American Thoracic Society (ATS)/European Respiratory Society (ERS) guidelines [36]. All curves were checked *post hoc* by a specialist to ensure that satisfactory reproducibility criteria had been met. The parameters included in this analysis were FVC as a measure of lung volume and size, and FEV₁ and forced expiratory flow between 25% and 75% of FVC (FEF_{25–75%}) as measures of airway obstruction and small airways narrowing, respectively. Higher values in these parameters represent better lung function and respiratory health [10]. Values for all parameters correspond to the predicted volume values for FVC and FEV₁ (L) and FEF_{25–75%} (L·s^{−1}) and were calculated based on the Global Lung Function Initiative (GLI) 2012 reference data [37] using GLI-2012 Excel sheet calculator.

Exposure assessment

Greenness

The assessment of greenness was based on the mean Normalised Difference Vegetation Index (NDVI) within 100, 250 and 500 m of the child's residence at birth, four, seven and 10 years of age. These buffer sizes were selected to cover immediate and more distant areas of exposure [38]. The NDVI was calculated based on land surface reflectance of visible red and near-infrared wavelengths. The values range between −1 (water) and 1, with higher positive values indicating denser green vegetation. Only images with ≤5% cloud coverage from Landsat 5 and 8 (spatial resolution: 30 m) during the spring/summer period (peak of vegetation) of the assessment years (2005/2006, 2009/2011, 2012/2014 and 2015/2017) were used, as previously described in G21 cohort studies [38]. Negative NDVI values were omitted from the calculation. ArcMap 10.5 was used to process satellite images, and QGIS 3.8 was used to extract the average NDVI.

Proximity, accessibility and number of urban green spaces

To determine residential proximity and number of UGS, all public and free-to-access UGS in the Porto Metropolitan Area (n=662) were included, without restrictions regarding size, location or any particular characteristic. The UGS included public green spaces, such as urban parks, gardens and proximity green spaces, which are administered by the city councils of Porto Metropolitan Area or privately owned, but freely accessible to the public. The cartography was obtained from digital maps provided by the different city halls of Porto Metropolitan Area. Similar to previous studies [38], using the location of each child's residence at birth, four, seven and 10 years of age, the following network-based measures were calculated: 1) accessibility of UGS within 400 and 800 m from the residence (yes/no); 2) number of green spaces available within 400 and 800 m from the residence (count); and 3) proximity to the nearest green space (km). When UGS were delimited (*i.e.* with fencing), the distance to the entrance was considered; otherwise, the distance to the nearest boundary was used. For calculations, ArcGIS version 10.5 software and the Network Analyst extension was used, applying an updated street network dataset provided by the Environmental Systems Research Institute.

Proximity to blue spaces

The Portuguese Water Atlas (from the Portuguese “Atlas da Água”) was used to assess the Euclidean distance of children's residence to the nearest blue space, including only the sea and rivers, as described previously [38]. Other water bodies, including urban water sources such as fountains, ponds and lakes were not included, due to their small size.

Covariates

A comprehensive set of covariates was selected based on previous studies on associations between lung function and personal and environmental factors [39–41]. The following variables were considered: sex, age in months, total physical activity, outdoor levels of nitrogen dioxide (NO₂), maternal educational level, household monthly income, population density and neighbourhood socioeconomic deprivation.

The practice of physical activity was defined as engagement (yes or no) in physical exercise, and active leisure activities, performed on a repeated and regular basis (“Does (child's name) engage in any type of repeated and regular physical exercise outside of school?”).

Maternal educational level was measured in years of schooling and categorised into three classes: primary (≤9 years of education, secondary and tertiary (≥13 years). Household monthly income was collected as a categorical variable and grouped into three classes: ≤EUR 1000, EUR 1001–1500 and >EUR 1500.

Population density at the neighbourhood level (corresponding to the census tract, which in Portugal holds ~300 residences) [42] was obtained from the Portuguese National Institute of Statistics 2011 [43]. Neighbourhood socioeconomic deprivation was measured at the census tract level using the European Deprivation Index, with lower values corresponding to least deprived areas [44].

Outdoor levels of NO₂ (µg·m⁻³) were obtained from AirBase, the European air quality database from the European Environment Agency (EEA) [45]. The EEA provides 1-km grids for NO₂, which were created based on monitoring station data (more details can be found in the supplementary material). Each participant was assigned the residential point location grid value.

Statistical analysis

Three models were used to assess the effect of green (NDVI, proximity and number of UGS) and blue spaces on lung function at 10 years of age: 1) averaged exposure; 2) early-life exposure (*i.e.* exposure at time 0); and 3) exposure trend over time (from birth to 10 years of age).

In the first model, the exposure variables were averaged from birth to 10 years of age. The accessibility of UGS within 400 and 800 m from the residence was operationalised as a categorical variable that distinguishes children who had access to UGS in the majority of the cohort evaluations (three or more times from birth to 10 years of age) from those who had access in half of the cohort evaluations or less (two or fewer times).

In the second and third models, a two-step analysis based on the results derived from a child's individual exposure curve was performed [46]. For these models, we firstly calculated the intercept and slope parameters (first step), and then we used the intercept for model 2 and the slope for model 3 (second step). In the first step, a regression analysis was performed with age (in days) to lung function assessment as the independent variable and the exposure as the dependent variable (linear regression for continuous variables and logistic regression for dichotomous variables). This regression analysis was performed with the exposure data from birth to the age of 10 years for each child separately in a long-structured dataset to obtain child-specific exposure curves. Secondly, the calculated intercept parameter (*i.e.* exposure at time 0) from the first step was included in the new model as an estimate of the early-life exposure, capturing how much between-child variability exists in terms of where they start [47]. The slope coefficient (representing the trend of the child's change in exposure over time) was included in this new model to predict lung function parameters at 10 years. The intercept and slope parameters jointly define the underlying exposure trajectory. We also added the standard error of the intercept and slope parameters from the first step to the new model as an indication of fluctuation of the actual exposure measurements. In these models, the longitudinally time-varying exposure was first modelled as a function of time by calculating intercepts and slopes, and then the estimates of these coefficients were used as predictors in the linear regression model. The step-by-step sequence of the statistical analyses is summarised in supplementary figure S2.

Linear regressions models were fitted to estimate the crude and adjusted associations and we expressed the estimates for a standard deviation change in exposures. Adjusted models included the covariates listed in the previous section and identified based on direct acyclic graph (developed using the R package "dagitty") (supplementary figure S3). Results were expressed as β-coefficients (β) and 95% confidence intervals.

The mediation effects of physical activity and outdoor levels of NO₂ were calculated based on the structural equation modelling (SEM). SEM methods are based on path analysis and simultaneously test both direct and indirect effects of predictive variables on the outcome [48]. A SEM was fitted using logistic regression analysis to estimate the indirect effects of physical activity and outdoor levels of NO₂ (R package "lavaan"). Effect modification by indicators of socioeconomic position was explored by assessing the statistical significance of multiplicative interactions, using likelihood ratio tests by comparing models with and without interaction terms [49, 50]. The analyses revealed no statistically significant interaction effects and, thus, results were presented without stratification for indicators of socioeconomic position. Additionally, to assess the robustness of the associations found in the main analyses, sensitivity analyses were performed using other buffer sizes (250 and 500 m), adjusting for residential mobility and for birthweight (supplementary tables S1, S2 and S3, respectively). Statistical analysis was performed using R software version 3.6.2.

Results

The study participants' characteristics are presented in table 1. The median (interquartile range) NDVI within 100 m increased slightly over time (from 0.148 at birth to 0.203 (0.163–0.251) at 10 years of age; table 2). The median distance to the nearest green space also increased over time (from 0.90 (0.49–1.50) km

TABLE 1 Characteristics of participants (Generation XXI; n=3278)

At birth	
Female	1654 (50.5)
Maternal education	
Primary (≤ 9 years)	1372 (41.9)
Secondary (10–12 years)	962 (29.3)
Tertiary (>12 years)	944 (28.8)
Household monthly income (EUR)	
≤ 1000	1060 (34.7)
1001–1500	895 (29.3)
>1500	1101 (36.0)
Neighbourhood socioeconomic deprivation	–0.02 $\pm$ 2.65
At 10 years	
BMI ($\text{kg}\cdot\text{m}^{-2}$)	18.3 (16.4–21.0)
Physically active (yes)	2079 (63.5)
FVC before bronchodilation (L)	2.24 $\pm$ 0.36
FEV ₁ before bronchodilation (L)	2.01 $\pm$ 0.31
FEF _{25–75%} before bronchodilation ($\text{L}\cdot\text{s}^{-1}$)	2.36 $\pm$ 0.52
Outdoor levels of NO ₂ ($\mu\text{g}\cdot\text{m}^{-3}$)	23.7 (20.2–26.8)

Data are presented as n (%), mean $\pm$ sd or median (interquartile range). BMI: body mass index; FVC: forced vital capacity; FEV₁: forced expiratory volume in 1 s; FEF_{25–75%}: forced expiratory flow between 25% and 75% of the FVC; NO₂: nitrogen dioxide.

at birth to 0.94 (0.51–1.53) km at 10 years of age; table 2). Almost 18% of the children lived within 400 m from a UGS and 40% lived within 800 m from a UGS over time. The median distance to the nearest blue space ranged from 4.80 (3.34–6.69) km at birth to 4.94 (3.44–6.76) km at 10 years of age (table 2).

Table 3 presents the crude and adjusted associations between NDVI and lung function at the age of 10 years. Early-life exposure to greenness was associated with higher values of FVC, FEV₁ and FEF_{25–75%}. However, after adjustment, the positive association between early-life exposure to NDVI and lung function parameters was no longer statistically significant (table 3). Differently, increasing NDVI values within 100 m from the residence were, even after adjustment, associated with higher values of FEV₁ (L) and FEF_{25–75%} ($\text{L}\cdot\text{s}^{-1}$) (β 0.01, 95% CI 0.0002–0.03 and β 0.02, 95% CI 0.001–0.05, respectively) (table 3). Although nonsignificant, a similar trend was observed between NDVI within 250 m and 500 m and lung function parameters (supplementary table S1). No significant associations were observed for the remaining life-course measures of green and blue space exposure (tables 4–7). The associations between proximity, accessibility and number of urban green spaces and proximity to blue spaces and lung function parameters remained the same when adjusted for residential mobility (supplementary table S2) and also for birthweight (supplementary table S3). The mediation analysis (table 8) revealed that associations between green and blue spaces and lung function do not seem to be mediated by physical activity and outdoor levels of NO₂.

TABLE 2 Measures of exposure to green and blue spaces in the residential neighbourhood (Generation XXI; n=3278)

	At birth	At 4 years	At 7 years	At 10 years
NDVI				
100 m	0.148 (0.105–0.205)	0.171 (0.124–0.226)	0.199 (0.160–0.245)	0.203 (0.163–0.251)
250 m	0.190 (0.143–0.251)	0.206 (0.160–0.266)	0.227 (0.187–0.273)	0.231 (0.191–0.279)
500 m	0.212 (0.166–0.273)	0.228 (0.180–0.284)	0.242 (0.200–0.285)	0.247 (0.204–0.290)
Accessibility to green spaces within 400 m (yes)	606 (18.5)	604 (18.4)	605 (18.5)	597 (18.2)
Number of green spaces within 400 m [#]	1.26 (1–4)	1.25 (1–4)	1.24 (1–5)	1.26 (1–5)
Accessibility to green spaces within 800 m (yes)	1473 (44.9)	1425 (43.5)	1422 (43.4)	1430 (43.6)
Number of green spaces within 800 m [#]	2.11 (1–9)	2.07 (1–9)	2.09 (1–9)	2.12 (1–9)
Distance to the nearest green space (km)	0.90 (0.49–1.50)	0.94 (0.50–1.51)	0.95 (0.50–1.52)	0.94 (0.51–1.53)
Distance to the nearest blue spaces (km)	4.80 (3.34–6.69)	4.94 (3.43–6.77)	4.93 (3.43–6.76)	4.94 (3.44–6.76)

Data are presented as median (interquartile range) or n (%), unless otherwise stated. NDVI: Normalised Difference Vegetation Index. [#]: mean (range).

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TABLE 3 Associations between Normalised Difference Vegetation Index (NDVI) within 100 m and lung function parameters at 10 years of age (Generation XXI; n=3278)

	Crude model	Adjusted model [#]
Averaged exposure		
FVC (L)	0.0101 (−0.0023–0.0225)	0.0030 (−0.0110–0.0169)
FEV ₁ (L)	0.0025 (−0.0051–0.0101)	−0.0019 (−0.0097–0.0060)
FEF _{25–75%} (L·s ^{−1})	0.0051 (−0.0021–0.0123)	−0.0016 (−0.0084–0.0052)
Early-life exposure		
FVC (L)	0.0246 (0.0032–0.0291)*	0.0137 (−0.0063–0.0303)
FEV ₁ (L)	0.0150 (0.0071–0.0342)*	0.0147 (−0.0023–0.0030)
FEF _{25–75%} (L·s ^{−1})	0.0218 (0.0043–0.0480)*	0.0247 (−0.0093–0.0403)
Exposure trend over time		
FVC (L)	0.0237 (0.0020–0.0345)*	0.0094 (−0.0032–0.0330)
FEV ₁ (L)	0.0238 (0.0041–0.0264)**	0.0146 (0.0002–0.0319)**
FEF _{25–75%} (L·s ^{−1})	0.0320 (0.0044–0.0509)*	0.0201 (0.0014–0.0505)*

Data are presented as β (95% confidence interval). Bold type denotes statistical significance. FVC: forced vital capacity; FEV₁: forced expiratory volume in 1 s; FEF_{25–75%}: forced expiratory flow between 25% and 75% of the FVC. #: adjusted for sex, age in months, maternal education, household monthly income, population density and neighbourhood socioeconomic deprivation. *: p<0.05; **: p<0.01.

TABLE 4 Associations between the accessibility to green spaces and lung function parameters at 10 years of age (Generation XXI; n=3278)

	Crude model	Adjusted model [#]
Averaged exposure		
FVC (L)	−0.0016 (−0.0277–0.0244)	−0.0056 (−0.0294–0.0182)
FEV ₁ (L)	−0.0039 (−0.024–0.016)	−0.0052 (−0.024–0.014)
FEF _{25–75%} (L·s ^{−1})	−0.0191 (−0.0385–0.0004)	−0.0042 (−0.0208–0.0125)
Early-life exposure		
FVC (L)	−0.0043 (−0.014–0.0056)	−0.0067 (−0.016–0.0024)
FEV ₁ (L)	−0.0045 (−0.0123–0.0032)	−0.0054 (−0.0126–0.0019)
FEF _{25–75%} (L·s ^{−1})	−0.010 (−0.0177–−0.0029)*	−0.0047 (−0.011–0.0016)
Exposure trend over time		
FVC (L)	0.0026 (−0.0073–0.0126)	0.0037 (−0.0054–0.0128)
FEV ₁ (L)	0.0016 (−0.0062–0.0093)	0.0029 (−0.0044–0.0102)
FEF _{25–75%} (L·s ^{−1})	−0.0010 (−0.0088–0.0059)	0.0024 (−0.0040–0.0087)
Accessibility to green spaces within 800 m		
Averaged exposure		
FVC (L)	0.0066 (−0.0130–0.0262)	0.0077 (−0.0104–0.0258)
FEV ₁ (L)	0.0040 (−0.0114–0.0194)	0.0062 (−0.0085–0.0205)
FEF _{25–75%} (L·s ^{−1})	−0.0035 (−0.0181–0.0111)	0.0055 (−0.0072–0.0181)
Early-life exposure		
FVC (L)	−0.0004 (−0.0102–0.096)	0.0005 (−0.0086–0.0097)
FEV ₁ (L)	−0.0011 (−0.0088–0.0066)	0.0003 (−0.0070–0.0077)
FEF _{25–75%} (L·s ^{−1})	−0.0055 (−0.0128–0.0019)	0.0005 (−0.0059–0.0068)
Exposure trend over time		
FVC (L)	−0.0048 (−0.0146–0.0051)	−0.0003 (−0.0093–0.0086)
FEV ₁ (L)	−0.0036 (−0.0114–0.041)	−0.0003 (−0.0075–0.0069)
FEF _{25–75%} (L·s ^{−1})	−0.0026 (−0.0099–0.0048)	−0.0079 (−0.0059–0.0055)

Data are presented as β (95% confidence interval). Bold type denotes statistical significance. FVC: forced vital capacity; FEV₁: forced expiratory volume in 1 s; FEF_{25–75%}: forced expiratory flow between 25% and 75% of the FVC. #: adjusted for sex, age in months, maternal education, household monthly income, population density and neighbourhood socioeconomic deprivation. *: p<0.05.

Discussion

Increasing exposure to greenness over time within a radius of 100 m of the residence between birth and 10 years of age had a positive association with lung function at 10 years of age; more precisely, in FEV_1 and $FEF_{25-75\%}$, markers of airway obstruction and small airways narrowing, respectively. Measures of accessibility to urban green spaces and blue spaces did not seem to influence lung function.

TABLE 5 Associations between the number of green spaces and lung function parameters at 10 years of age (Generation XXI; n=3278)

	Crude model	Adjusted model [#]
Averaged exposure		
FVC (L)	-0.0023 (-0.0207–0.0162)	-0.0009 (-0.0177–0.01594)
FEV_1 (L)	-0.0014 (-0.016–0.0131)	-0.0006 (-0.0141–0.0129)
$FEF_{25-75\%}$ (L·s ⁻¹)	0.0020 (-0.0121–0.0161)	-0.0001 (-0.0119–0.0117)
Early-life exposure		
FVC (L)	-0.0035 (-0.0222–0.0152)	-0.0019 (-0.02–0.0148)
FEV_1 (L)	-0.0023 (-0.0170–0.0123)	-0.0017 (-0.0154–0.0119)
$FEF_{25-75\%}$ (L·s ⁻¹)	0.0016 (-0.0127–0.0159)	-0.0010 (-0.0129–0.0110)
Exposure trend over time		
FVC (L)	-0.0039 (-0.0226–0.0148)	-0.0045 (-0.0218–0.0128)
FEV_1 (L)	-0.0031 (-0.0178–0.0116)	-0.0037 (-0.0176–0.0102)
$FEF_{25-75\%}$ (L·s ⁻¹)	-0.0033 (-0.0175–0.0110)	-0.0047 (-0.0169–0.0074)
Number of green spaces within 800 m		
Averaged exposure		
FVC (L)	-0.0066 (-0.0220–0.0088)	-0.0015 (-0.0156–0.0127)
FEV_1 (L)	-0.0053 (-0.0174–0.0067)	-0.0012 (-0.0125–0.0102)
$FEF_{25-75\%}$ (L·s ⁻¹)	-0.0055 (-0.0169–0.0059)	-0.0018 (-0.0117–0.0082)
Early-life exposure		
FVC (L)	-0.0059 (-0.0193–0.0075)	-0.0016 (-0.0139–0.0108)
FEV_1 (L)	-0.0047 (-0.0152–0.0058)	-0.0013 (-0.0112–0.0087)
$FEF_{25-75\%}$ (L·s ⁻¹)	-0.0048 (-0.0147–0.0052)	-0.0018 (-0.0104–0.0068)
Exposure trend over time		
FVC (L)	0.0015 (-0.0119–0.0149)	0.0025 (-0.0021–0.0071)
FEV_1 (L)	0.0008 (-0.0097–0.0113)	0.0053 (-0.0047–0.0153)
$FEF_{25-75\%}$ (L·s ⁻¹)	-0.0013 (-0.0113–0.0086)	0.0039 (-0.0047–0.0126)

Data are presented as β (95% confidence interval). FVC: forced vital capacity; FEV_1 : forced expiratory volume in 1 s; $FEF_{25-75\%}$: forced expiratory flow between 25% and 75% of the FVC. #: adjusted for sex, age in months, maternal education, household monthly income, population density and neighbourhood socioeconomic deprivation.

TABLE 6 Associations between the distance to the nearest green space (km) and lung function parameters at 10 years of age (Generation XXI; n=3278)

	Crude model	Adjusted model [#]
Averaged exposure		
FVC (L)	-0.003 (-0.013–0.006)	-0.006 (-0.015–0.004)
FEV_1 (L)	-0.002 (-0.009–0.006)	-0.004 (-0.012–0.003)
$FEF_{25-75\%}$ (L·s ⁻¹)	0.004 (-0.003–0.011)	-0.004 (-0.010–0.003)
Early-life exposure		
FVC (L)	-0.003 (-0.013–0.007)	-0.005 (-0.014–0.004)
FEV_1 (L)	-0.001 (-0.009–0.006)	-0.004 (-0.011–0.003)
$FEF_{25-75\%}$ (L·s ⁻¹)	0.005 (-0.003–0.012)	-0.003 (-0.009–0.003)
Exposure trend over time		
FVC (L)	-0.005 (-0.014–0.005)	-0.004 (-0.013–0.005)
FEV_1 (L)	-0.004 (-0.011–0.004)	-0.003 (-0.010–0.004)
$FEF_{25-75\%}$ (L·s ⁻¹)	-0.003 (-0.010–0.005)	-0.002 (-0.008–0.004)

Data are presented as β (95% confidence interval). FVC: forced vital capacity; FEV_1 : forced expiratory volume in 1 s; $FEF_{25-75\%}$: forced expiratory flow between 25% and 75% of the FVC. #: adjusted for sex, age in months, maternal education, household monthly income, population density and neighbourhood socioeconomic deprivation.

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TABLE 7 Associations between the distance to the nearest blue space (km) and lung function parameters at 10 years of age (Generation XXI; n=3278)

	Crude model	Adjusted model [#]
Averaged exposure		
FVC (L)	-0.0028 (-0.0124–0.0069)	0.0002 (-0.0088–0.0091)
FEV ₁ (L)	-0.0015 (-0.0091–0.0061)	0.0004 (-0.0068–0.0075)
FEF _{25–75%} (L·s ⁻¹)	0.0013 (-0.0059–0.0085)	0.0004 (-0.0061–0.0063)
Early-life exposure		
FVC (L)	-0.0025 (-0.0121–0.0072)	0.0007 (-0.0082–0.0097)
FEV ₁ (L)	-0.0012 (-0.0089–0.0063)	0.0008 (-0.0064–0.0080)
FEF _{25–75%} (L·s ⁻¹)	0.0016 (-0.0056–0.0088)	0.0009 (-0.0054–0.0071)
Exposure trend over time		
FVC (L)	-0.0030 (-0.0127–0.0067)	-0.0033 (-0.0122–0.0056)
FEV ₁ (L)	-0.0022 (-0.0096–0.0054)	-0.0025 (-0.0096–0.0046)
FEF _{25–75%} (L·s ⁻¹)	-0.0015 (-0.0087–0.0058)	-0.0024 (-0.0086–0.0038)

Data are presented as β (95% confidence interval). FVC: forced vital capacity; FEV₁: forced expiratory volume in 1 s; FEF_{25–75%}: forced expiratory flow between 25% and 75% of the FVC. [#]: adjusted for sex, age in months, maternal education, household monthly income, population density and neighbourhood socioeconomic deprivation.

These results suggest that an increasing exposure trend over time to greenness is associated with better lung function. The results are in line with our initial hypothesis, and match those of previous studies [28, 29]. Hence, moving to greener areas and increasing the amount of vegetation may be a possible strategy to improve the lung function of children. However, this effect was only visible when considering a 100-m buffer around the residence, which suggests that the observed effect is dependent upon the residential area considered. Nevertheless, previous studies have shown that vegetation measured within larger buffers may also predict health outcomes including those related with respiratory health [20, 24].

Early-life exposure to greenness was not as relevant as the exposure trend over time, which may indicate that this period is not particularly sensitive to the exposure to green spaces. This may happen because newborns are seldom exposed to outdoor environments. The daily amount of time spent at home by newborns is nearly 90% [51]. Conversely, exposure to indoor (rather than outdoor) biological, physical and chemical agents, which we do not have information about, may be more relevant at early life stages. These results may suggest that the time-varying exposure to greenness may have a protective effect on lung. While the underlying pathways for such association was not addressed in the present study, these results may be related to psychosocial mechanisms, moving to greener neighbourhoods and interventions to make neighbourhoods greener, have both been associated with better mental health in adults [52], and consequently to better physical health, including respiratory health [53]. This mechanism might explain the observed association between NDVI exposure trend over time and lung function. However, the mediation effect of mental health was not assessed, since no information on child mental health is available in the G21 cohort. Additionally, averaged exposure to greenness was unrelated to lung function, contrasting with the results from a recent study, which also included an adult population, where lifetime average greenness within a 100-m buffer was associated with better lung function at 24 years [29].

The lack of association with the measures of accessibility to UGS was not in line with our initial hypothesis (this result is consistent even when the variable accessibility of UGS is categorised differently; supplementary table S4), although it corroborates previous findings [18, 27]. Evidence suggests that the beneficial effect of UGS can be offset by possible negative aspects: 1) specific characteristics of the flora can have a deleterious effect on respiratory health by inducing chronic airway inflammation [54]; 2) lack of biodiversity [55]; and 3) areas where UGS are present could have higher pollution levels [20].

No associations were found between accessibility to blue spaces and lung function. A prior study highlighted the positive effect of blue space on respiratory health by reducing air pollution, and aerosolised waterfalls had a beneficial effect on asthma [31]. The lack of association may be partially due to the effect being limited to very close distances and, in our sample, the number of children living within walking distances (e.g. 400 m, 800 m) of those spaces is limited (no children lived <400 m from a blue space and only 29, that is, <1%, lived at a distance of ≤800 m).

Several mechanisms may be related in the association between greenness and lung function. The mediation analysis revealed that associations between greenness and lung function do not seem to be mediated by

TABLE 8 Path coefficients estimated in a structural equation model predicting the indirect effects of physical activity and outdoor levels of nitrogen dioxide (NO₂) on lung function at 10 years of age

	Indirect effect of physical activity	Indirect effect of outdoor levels of NO ₂
NDVI within 100 m		
Averaged exposure		
FVC (L)	0.001 (−0.001–0.001)	0.001 (−0.001–0.001)
FEV ₁ (L)	0.001 (−0.001–0.001)	0.001 (−0.001–0.001)
FEF _{25–75%} (L·s ^{−1})	0.001 (−0.001–0.001)	0.001 (−0.001–0.001)
Early-life exposure		
FVC (L)	−0.001 (−0.005–0.006)	0.02 (−0.05–0.09)
FEV ₁ (L)	−0.001 (−0.004–0.005)	0.02 (−0.04–0.07)
FEF _{25–75%} (L·s ^{−1})	−0.001 (−0.003–0.004)	0.02 (−0.03–0.07)
Exposure trend over time		
FVC (L)	0.75 (−11.3–12.8)	−34.6 (−146.5–77.3)
FEV ₁ (L)	0.60 (−9.05–10.3)	−35.6 (−125.5–54.3)
FEF _{25–75%} (L·s ^{−1})	0.47 (−7.18–8.12)	−42.7 (−121.2–35.9)
Accessibility to green spaces within 400 m		
Averaged exposure		
FVC (L)	−0.0001 (−0.001–0.001)	−0.0001 (−0.005–0.004)
FEV ₁ (L)	−0.0001 (−0.001–0.0001)	−0.0001 (−0.004–0.003)
FEF _{25–75%} (L·s ^{−1})	−0.0001 (−0.001–0.0001)	−0.001 (−0.004–0.002)
Early-life exposure		
FVC (L)	−0.0001 (−0.001–0.001)	−0.0001 (−0.004–0.003)
FEV ₁ (L)	−0.0001 (−0.001–0.0001)	−0.0001 (−0.003–0.003)
FEF _{25–75%} (L·s ^{−1})	−0.0001 (−0.001–0.0001)	−0.001 (−0.003–0.002)
Exposure trend over time		
FVC (L)	0.07 (−0.11–0.25)	−0.11 (−0.54–0.32)
FEV ₁ (L)	−0.06 (−0.08–0.20)	−0.10 (−0.45–0.25)
FEF _{25–75%} (L·s ^{−1})	0.05 (−0.07–0.16)	−0.12 (−0.43–0.19)
Number of green spaces within 400 m		
Averaged exposure		
FVC (L)	0.0001 (−0.001–0.002)	0.0001 (−0.001–0.001)
FEV ₁ (L)	0.0001 (−0.001–0.002)	0.0001 (−0.001–0.001)
FEF _{25–75%} (L·s ^{−1})	0.0001 (−0.001–0.001)	−0.0001 (−0.001–0.001)
Early-life exposure		
FVC (L)	−0.0001 (−0.001–0.001)	−0.0001 (−0.001–0.001)
FEV ₁ (L)	0.0001 (−0.001–0.001)	−0.0001 (−0.001–0.001)
FEF _{25–75%} (L·s ^{−1})	−0.0001 (−0.001–0.001)	−0.0001 (−0.001–0.001)
Exposure trend over time		
FVC (L)	0.26 (−0.41–0.93)	0.003 (−0.08–0.09)
FEV ₁ (L)	0.21 (−0.33–0.74)	0.002 (−0.07–0.07)
FEF _{25–75%} (L·s ^{−1})	0.15 (−0.31–0.62)	−0.005 (−0.08–0.07)
Accessibility to green spaces within 800 m		
Averaged exposure		
FVC (L)	−0.0001 (−0.001–0.001)	−0.002 (−0.006–0.003)
FEV ₁ (L)	−0.0001 (−0.001–0.0001)	−0.001 (−0.005–0.003)
FEF _{25–75%} (L·s ^{−1})	−0.0001 (−0.001–0.0001)	−0.002 (−0.005–0.002)
Early-life exposure		
FVC (L)	−0.0001 (−0.001–0.001)	−0.001 (−0.006–0.004)
FEV ₁ (L)	−0.001 (−0.005–0.003)	−0.0001 (−0.001–0.001)
FEF _{25–75%} (L·s ^{−1})	−0.0001 (−0.001–0.001)	−0.001 (−0.005–0.002)
Exposure trend over time		
FVC (L)	0.09 (−0.08–0.25)	−0.10 (−0.64–0.43)
FEV ₁ (L)	0.07 (−0.06–0.20)	−0.09 (−0.52–0.34)
FEF _{25–75%} (L·s ^{−1})	0.06 (−0.05–0.16)	−0.12 (−0.50–0.26)
Number of green spaces within 800 m		
Averaged exposure		
FVC (L)	0.0001 (−0.001–0.001)	−0.0001 (−0.001–0.001)
FEV ₁ (L)	0.0001 (−0.001–0.001)	−0.0001 (−0.001–0.001)
FEF _{25–75%} (L·s ^{−1})	0.0001 (−0.001–0.001)	−0.0001 (−0.001–0.001)

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TABLE 8 Continued

	Indirect effect of physical activity	Indirect effect of outdoor levels of NO ₂
Early-life exposure		
FVC (L)	−0.0001 (−0.001–0.001)	−0.0001 (−0.001–0.001)
FEV ₁ (L)	−0.0001 (−0.001–0.001)	−0.0001 (−0.001–0.001)
FEF _{25–75%} (L·s ^{−1})	−0.0001 (−0.001–0.001)	−0.0001 (−0.001–0.001)
Exposure trend over time		
FVC (L)	0.09 (−0.07–0.25)	−0.01 (−0.07–0.04)
FEV ₁ (L)	0.07 (−0.05–0.20)	−0.01 (−0.05–0.03)
FEF _{25–75%} (L·s ^{−1})	0.05 (−0.05–0.16)	−0.01 (−0.05–0.03)
Proximity to the nearest green space (km)		
Averaged exposure		
FVC (L)	−0.0001 (−0.004–0.004)	0.03 (−0.03–0.08)
FEV ₁ (L)	−0.0001 (−0.003–0.003)	0.02 (−0.02–0.07)
FEF _{25–75%} (L·s ^{−1})	−0.0001 (−0.003–0.002)	0.02 (−0.01–0.06)
Early-life exposure		
FVC (L)	0.0001 (−0.004–0.005)	0.02 (−0.03–0.06)
FEV ₁ (L)	0.0001 (−0.003–0.004)	0.02 (−0.02–0.05)
FEF _{25–75%} (L·s ^{−1})	0.0001 (−0.002–0.003)	0.02 (−0.02–0.05)
Exposure trend over time		
FVC (L)	−0.55 (−1.62–0.51)	1.41 (−3.88–6.71)
FEV ₁ (L)	−0.44 (−1.30–0.41)	1.23 (−3.03–5.49)
FEF _{25–75%} (L·s ^{−1})	−0.35 (−1.05–0.35)	1.50 (−2.22–5.23)
Distance to blue spaces (km)		
Averaged exposure		
FVC (L)	0.0001 (−0.001–0.001)	0.0001 (−0.001–0.001)
FEV ₁ (L)	0.0001 (−0.001–0.001)	0.0001 (−0.001–0.001)
FEF _{25–75%} (L·s ^{−1})	0.0001 (−0.001–0.001)	0.0001 (−0.001–0.001)
Early-life exposure		
FVC (L)	0.0001 (−0.001–0.001)	0.0001 (−0.001–0.001)
FEV ₁ (L)	0.0001 (−0.001–0.001)	0.0001 (−0.001–0.001)
FEF _{25–75%} (L·s ^{−1})	0.0001 (−0.001–0.001)	0.0001 (−0.001–0.001)
Exposure trend over time		
FVC (L)	0.11 (−0.13–0.34)	−0.39 (−1.59–0.81)
FEV ₁ (L)	0.09 (−0.10–0.27)	−0.33 (−1.29–0.63)
FEF _{25–75%} (L·s ^{−1})	0.07 (−0.08–0.22)	−0.39 (−1.23–0.46)

Data are presented as β (95% confidence interval). NDVI: normalised difference vegetation index; FVC: forced vital capacity; FEV₁: forced expiratory volume in 1 s; FEF_{25–75%}: forced expiratory flow between 25% and 75% of the FVC.

physical activity or outdoor levels of NO₂. However, vegetation may reduce the levels of other air pollutants (particulate matter, ozone), which are known to have a deleterious effect on lung function [56]. Moreover, the contact with the natural environment may promote an adequate stimulation of immunoregulatory processes [55], improving lung function and thus reducing the risk of chronic inflammatory diseases, such as asthma.

Although the observed effect estimates were relatively small, they may have important public health impacts, suggesting that the provision of green spaces in the residential neighbourhoods of metropolitan areas may be an effective strategy to improve lung function in children, which in turn may prevent the development of chronic respiratory disease. The provision of green spaces may also contribute to environmental benefits by reducing the emission of air pollutants, noise and temperature, and by preserving regional ecosystems and biodiversity [57]. Additionally, the results support the growing evidence regarding to the benefits of green spaces on child respiratory health, namely on lung function.

This study presents various limitations that merit further discussion. Accessibility was used as a proxy of utilisation of UGS, but there are other factors influencing utilisation (flora, availability of equipment, safety) [58]. The fact that biodiversity was not included in the analysis impairs an in-depth analysis of the effects of UGS (to understand if the null associations were due to a low variety of flora or a specific type of flora or another characteristic not considered) [17]. The slight variations in NDVI over time may reduce

the power of analysis, and consequently the likelihood of finding a significant association between exposure to NDVI over time and child lung function. Moreover, exposure assessment to blue spaces only included the distance to rivers and sea, excluding small water bodies such as fountains, ponds and lakes. A recent meta-analysis suggested that even smaller water bodies may have a beneficial impact on air pollution levels and cooling [59]. Some of the included studies also observed negative effects of blue spaces, including increased disease transmission and air pollution due to river dust [59]. Like in other cohort studies, losses to follow-up can introduce bias and limit external validity, and our sample may not fully represent the socioeconomic conditions and practice of physical activity of the initial cohort participants. In fact, the included participants differed in the following characteristics: the included children reported practising more physical activity (63.5% of included participants *versus* 59.0% of those excluded, $p=0.019$), lived in less deprived neighbourhoods (14.0% of included participants *versus* 12.1% of those excluded, $p<0.05$) and belonged to families with higher household monthly income (household monthly income >EUR 1500 was 36.0% in included participants *versus* 28.3% in those excluded, $p<0.05$) and with higher educational levels (maternal educational level >12 years was 28.8% in included participants *versus* 21.1% in those excluded, $p<0.05$) (supplementary table S5). The assessment of the different mediators also lacks resolution and detail. Although green spaces can promote physical activity, we lacked information to differentiate between indoor and outdoor activities. This can be important, because it has been hypothesised that physical activity in green spaces can be more beneficial than in other environments [60]. The mediation effect of air pollution was assessed only by NO₂ levels. However, other pollutants, such as particulate matter and ozone, have also been associated with children's lung function level and growth [56], but were not assessed in our study. Additionally, NO₂ was measured in raster cells of 1 km², which may decrease the resolution of the assessment of the mediation effect. In addition, the assessment of mediators and lung function parameters at the same time point may be associated to a risk of bias due to the lack of temporal order of the mediator(s) and the lung function [61]. However, several studies reported the assessment at the same time [61], and according to GOLDSMITH *et al.* [62], models with contemporaneous paths may also be fitted. Moreover, other covariates may also mediate the association between green spaces and lung function, such as biodiversity [55]. Several potential confounders have also been considered, including socioeconomic factors (maternal educational level, household monthly income, and neighbourhood socioeconomic deprivation). Previous studies have reported that green spaces may be differently distributed according to neighbourhood socioeconomic characteristics and that the effect of urban green spaces on health may also differ among different socioeconomic groups [57, 63]. In our study, we found no statistically significant interactions between nature exposures and socioeconomic indicators and associations persisted after adjustment for socioeconomic factors. However, our adjustment for socioeconomic factors may have been insufficient to capture true differences in socioeconomic characteristics over time, and further studies are needed to better understand the complex interaction between socioeconomic and environmental factors on lung function among children. Moreover, in our study we did not use any methods to deal with missing data, such as multiple imputation and inverse-probability weighting. The missing data on exposures and covariates (supplementary table S6) may reduce the power to detect change over time and may also be associated with under- or over-estimation of exposure effects. Additionally, the missing data may increase the possibility of selection bias, which may distort the observed associations. However, the missing values are low (6.8% for household monthly income) (supplementary table S6), and some authors have suggested that missing rates between 5% and 10% are generally less serious [64, 65].

This study brings various novelties to the study of the relationship between nature and respiratory health. To the best of our knowledge, this is the first study estimating the association between longitudinal accessibility to UGS and lung function in children. Furthermore, it is the first to use a comprehensive life-course approach in exposure assessment, assessing not only averaged exposures, but also early-life exposure (at birth) and exposure trends over time. To increase the evidence base on this emerging topic, future works should focus on having lung function measured in various moments in time to clarify lung function trajectories and inform about the importance of environmental factors at each phase. Additionally, more refined objective and subjective measures of green and blue space exposure about space quality, biodiversity and frequency and type of utilisation are recommended to use in future research.

Conclusions

In conclusion, increases in the exposure to vegetation across childhood were associated with higher lung function. However, no significant associations were found between proximity to urban green spaces, such as parks or gardens, or blue spaces, and lung function. While the underlying mechanism remains unknown, it brings about additional evidence that city greening may contribute to better respiratory health.

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Supplementary material

Green and blue spaces and lung function in the Generation XXI cohort: a life course approach

Figure S1 Participants evaluated in the Generation XXI cohort

Figure S2 Schematic representation of the statistical analysis workflow

Figure S3 The direct acyclic graph (DAG) for the association between green and blue spaces and lung function

Table S1 Associations (β , 95%CI) between NDVI within 250 and 500 m and lung function parameters at 10 years of age (Generation XXI, n=3278)

Table S2 Associations (β , 95%CI) between the NDVI, proximity, accessibility, and number of urban green spaces and proximity to blue spaces and lung function parameters at 10 years of age adjusted for residential mobility (Generation XXI, n=3278)

Table S3 Associations (β , 95%CI) between the NDVI, proximity, accessibility, and number of urban green spaces and proximity to blue spaces and lung function parameters at 10 years of age adjusted for birthweight (Generation XXI, n=3278)

Table S4 Associations (β , 95%CI) between the existence of green spaces and lung function parameters at 10 years of age (Generation XXI, n=3278) [4 times access to UGS vs. 1 time access to UGS from birth to 10 years of age]

Table S5 Characteristics of participants included and excluded (Generation XXI, n=3278)

Table S6 Missing data (Generation XXI, n=3278)

Methods

Outdoor levels of NO₂

The methodology for creating the concentration maps of NO₂ follows the two-step methodology developed in Horálek J, et al. [1]: a linear regression model on the basis of European wide station measurement data, followed by kriging of the residuals produced from that regression model (residual kriging). Supplementary data for linear regression include, among others, traffic, land uses, road typologies, and population density. Separate map layers are created for the rural and the urban background areas on a grid at 10x10 km resolution. The rural background map layer is based on the rural background stations and the urban background map layer on the urban and the suburban background stations. Subsequently, the rural background map layer and the urban background map layer are merged into one combined final map using a weighting procedure based on the population density grid at 1x1 km resolution.

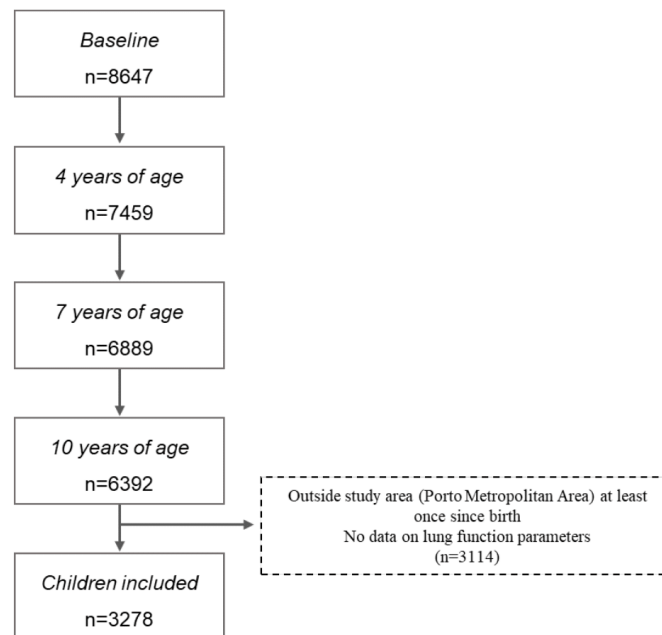


Figure S1 Participants evaluated in the Generation XXI cohort

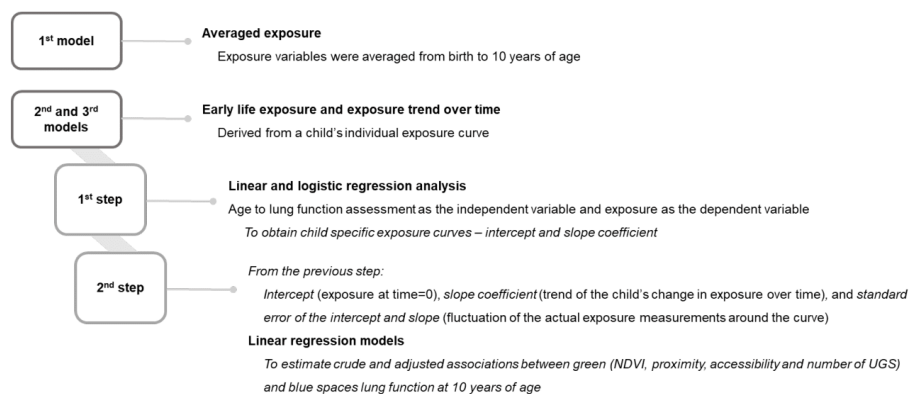


Figure S2 Schematic representation of the statistical analysis workflow

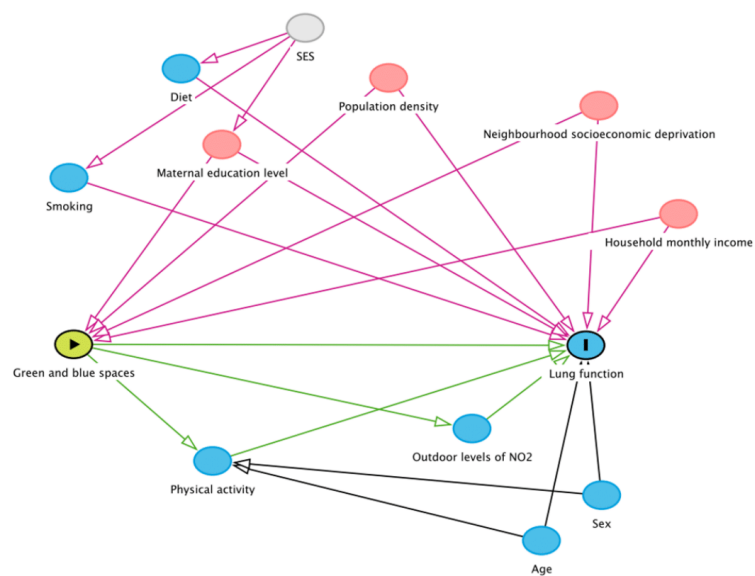


Figure S3 The direct acyclic graph (DAG) for the association between green and blue spaces and lung function

SES: socio-economic status; NO₂: nitrogen dioxide
 green circle with play symbol: exposure; blue circle with an I: outcome; blue circle: ancestor of outcome; pink circle: ancestor of exposure and outcome; dark grey circle: other variable; light grey circle: latent variable; green line: causal path; red line: biasing path

TABLE S1 Associations (β , 95%CI) between NDVI within 250 and 500 m and lung function parameters at 10 years of age (Generation XXI, n=3278)

	[β (95%CI)]	
	Crude model	Adjusted model*
NDVI within 250 m		
<i>Averaged exposure</i>		
FVC (L)	0.01 (-0.0002; 0.02)	0.008 (-0.006; 0.02)
FEV ₁ (L)	0.002 (-0.005; 0.01)	-0.001 (-0.009; 0.007)
FEF _{25%-75%} (L/s)	0.005 (-0.002; 0.01)	-0.0007 (-0.007; 0.006)
<i>Early life exposure</i>		
FVC (L)	0.02 (-0.0007; 0.03)	0.009 (-0.009; 0.03)
FEV ₁ (L)	0.02 (0.004; 0.03)	0.01 (-0.004; 0.03)
FEF _{25%-75%} (L/s)	0.03 (0.005; 0.05)	0.02 (-0.007; 0.04)
<i>Trend over time</i>		
FVC (L)	0.005 (-0.01; 0.02)	0.001 (-0.02; 0.02)
FEV ₁ (L)	0.007 (-0.007; 0.02)	0.004 (-0.01; 0.02)
FEF _{25%-75%} (L/s)	-0.02 (-0.006; 0.04)	0.02 (-0.007; 0.04)
NDVI within 500 m		
<i>Averaged exposure</i>		
FVC (L)	0.009 (-0.003; 0.02)	0.004 (-0.01; 0.02)
FEV ₁ (L)	0.01 (4.18e-6; 0.02)	0.004 (-0.008; 0.02)
FEF _{25%-75%} (L/s)	0.01 (-0.004; 0.03)	0.003 (-0.02; 0.02)
<i>Early life exposure</i>		
FVC (L)	0.01 (-0.004; 0.03)	0.002 (-0.01; 0.02)
FEV ₁ (L)	0.01 (0.0002; 0.02)	0.006 (-0.008; 0.02)
FEF _{25%-75%} (L/s)	0.02 (-0.003; 0.04)	0.007 (-0.02; 0.03)
<i>Trend over time</i>		
FVC (L)	0.004 (-0.01; 0.02)	0.002 (-0.01; 0.02)

FEV ₁ (L)	0.005 (-0.008; 0.02)	0.004 (-0.009; 0.02)
FEF _{25%-75%} (L/s)	0.009 (-0.01; 0.03)	0.008 (-0.01; 0.03)

NDVI: Normalized difference vegetation index; FVC: forced vital capacity; FEV₁: forced expiratory volume at the first second; FEF_{25%-75%}: forced expiratory flow between 25% and 75% of the FVC;

*adjusted for sex, age in months, maternal education, household monthly income, population density, and neighbourhood socioeconomic deprivation

TABLE S2 Associations (β , 95%CI) between the NDVI, proximity, accessibility, and number of urban green spaces and proximity to blue spaces and lung function parameters at 10 years of age adjusted for residential mobility (Generation XXI, n=3278)

	[β (95%CI)]		
	Crude model	Adjusted model (1)*	Adjusted model (2)*
NDVI within 100 m			
Averaged exposure			
FVC (L)	0.01 (-0.002; 0.02)	0.003 (-0.01; 0.02)	0.003 (-0.01; 0.02)
FEV ₁ (L)	0.003 (-0.005; 0.01)	-0.002 (-0.01; 0.006)	-0.002 (-0.01; 0.006)
FEF _{25%-75%} (L/s)	0.005 (-0.002; 0.01)	-0.002 (-0.008; 0.005)	-0.002 (-0.009; 0.005)
Early life exposure			
FVC (L)	0.02 (0.003; 0.03)	0.01 (-0.006; 0.03)	0.01 (-0.005; 0.02)
FEV ₁ (L)	0.02 (0.007; 0.03)	0.01 (-0.002; 0.003)	0.02 (-0.002; 0.003)
FEF _{25%-75%} (L/s)	0.02 (0.004; 0.05)	0.02 (-0.009; 0.04)	0.02 (-0.009; 0.03)
Exposure trend over time			
FVC (L)	0.02 (0.002; 0.03)	0.01 (-0.003; 0.03)	0.02 (-0.003; 0.03)
FEV ₁ (L)	0.02 (0.004; 0.03)	0.01 (0.0002; 0.03)	0.02 (0.0003; 0.03)
FEF _{25%-75%} (L/s)	0.03 (0.004; 0.05)	0.02 (0.001; 0.05)	0.02 (0.002; 0.05)
Accessibility to green spaces within 400 m			
Averaged exposure			
FVC (L)	-0.002 (-0.03; 0.02)	-0.006 (-0.03; 0.02)	-0.006 (-0.03; 0.02)
FEV ₁ (L)	-0.004 (-0.02; 0.02)	-0.005 (-0.02; 0.01)	-0.005 (-0.03; 0.02)
FEF _{25%-75%} (L/s)	-0.02 (-0.04; 0.0004)	-0.004 (-0.02; 0.01)	-0.005 (-0.02; 0.01)
Early life exposure			
FVC (L)	-0.004 (-0.01; 0.006)	-0.007 (-0.02; 0.002)	-0.00004 (-0.00009; 0.00001)
FEV ₁ (L)	-0.005 (-0.01; 0.003)	-0.005 (-0.01; 0.002)	-0.00003 (-0.00007; 0.00001)
FEF _{25%-75%} (L/s)	-0.01 (-0.02; -0.003)	-0.005 (-0.01; 0.002)	-0.00003 (-0.00006; 0.00001)
Exposure trend over time			
FVC (L)	0.003 (-0.007; 0.01)	0.004 (-0.005; 0.01)	0.004 (-0.005; 0.01)
FEV ₁ (L)	0.002 (-0.006; 0.009)	0.003 (-0.004; 0.01)	0.003 (-0.004; 0.01)
FEF _{25%-75%} (L/s)	-0.001 (-0.009; 0.006)	0.002 (-0.004; 0.009)	0.002 (-0.004; 0.009)
No. of green spaces within 400 m			
Averaged exposure			
FVC (L)	-0.002 (-0.02; 0.02)	-0.0009 (-0.02; 0.02)	-0.001 (-0.02; 0.02)
FEV ₁ (L)	-0.002 (-0.02; 0.01)	-0.0006 (-0.01; 0.01)	-0.0007 (-0.01; 0.01)
FEF _{25%-75%} (L/s)	0.002 (-0.01; 0.02)	-0.0001 (-0.01; 0.01)	-0.0002 (-0.01; 0.01)
Early life exposure			
FVC (L)	-0.004 (-0.02; 0.02)	-0.002 (-0.02; 0.01)	-0.002 (-0.02; 0.01)
FEV ₁ (L)	-0.002 (-0.02; 0.01)	-0.002 (-0.02; 0.01)	-0.002 (-0.02; 0.01)
FEF _{25%-75%} (L/s)	0.002 (-0.01; 0.02)	-0.001 (-0.01; 0.01)	-0.001 (-0.01; 0.01)
Exposure trend over time			
FVC (L)	-0.004 (-0.02; 0.01)	-0.005 (-0.02; 0.01)	-0.004 (-0.02; 0.01)
FEV ₁ (L)	-0.003 (-0.02; 0.01)	-0.004 (-0.02; 0.02)	-0.004 (-0.02; 0.01)

FEF _{25%-75%} (L/s)	-0.003 (-0.02; 0.01)	-0.005 (-0.02; 0.007)	-0.005 (-0.02; 0.007)
Accessibility to green spaces within 800 m			
Averaged exposure			
FVC (L)	0.007 (-0.01; 0.03)	0.008 (-0.01; 0.03)	0.007 (-0.01; 0.03)
FEV ₁ (L)	0.004 (-0.01; 0.02)	0.006 (-0.009; 0.02)	0.005 (-0.009; 0.02)
FEF _{25%-75%} (L/s)	-0.003 (-0.02; 0.01)	0.005 (-0.007; 0.02)	0.005 (-0.008; 0.02)
Early life exposure			
FVC (L)	-0.0004 (-0.01; 0.01)	0.0005 (-0.009; 0.01)	0.000004 (-0.00003; 0.00004)
FEV ₁ (L)	-0.002 (-0.02; 0.01)	0.0003 (-0.007; 0.008)	0.0006 (-0.007; 0.008)
FEF _{25%-75%} (L/s)	-0.005 (-0.01; 0.002)	0.0005 (-0.006; 0.007)	0.000003 (-0.00002; 0.00003)
Exposure trend over time			
FVC (L)	-0.004 (-0.01; 0.004)	-0.0003 (-0.008; 0.007)	-0.0005 (-0.008; 0.007)
FEV ₁ (L)	-0.003 (-0.01; 0.03)	-0.0003 (-0.006; 0.006)	-0.0006 (-0.008; 0.007)
FEF _{25%-75%} (L/s)	-0.005 (-0.008; 0.004)	-0.007 (-0.006; 0.005)	-0.0008 (-0.006; 0.004)
No. of green spaces within 800 m			
Averaged exposure			
FVC (L)	-0.007 (-0.02; 0.009)	-0.001 (-0.02; 0.01)	-0.001 (-0.02; 0.01)
FEV ₁ (L)	-0.005 (-0.02; 0.007)	-0.001 (-0.01; 0.01)	-0.0009 (-0.01; 0.01)
FEF _{25%-75%} (L/s)	-0.005 (-0.02; 0.006)	-0.002 (-0.01; 0.008)	-0.002 (-0.01; 0.008)
Early life exposure			
FVC (L)	-0.006 (-0.02; 0.008)	-0.002 (-0.01; 0.01)	-0.001 (-0.01; 0.01)
FEV ₁ (L)	-0.005 (-0.02; 0.006)	-0.001 (-0.01; 0.009)	-0.001 (-0.01; 0.009)
FEF _{25%-75%} (L/s)	-0.005 (-0.01; 0.005)	-0.002 (-0.01; 0.007)	-0.002 (-0.01; 0.007)
Exposure trend over time			
FVC (L)	0.002 (-0.01; 0.01)	0.007 (-0.006; 0.02)	0.007 (-0.006; 0.02)
FEV ₁ (L)	0.0008 (-0.01; 0.01)	0.005 (-0.005; 0.02)	0.005 (-0.005; 0.02)
FEF _{25%-75%} (L/s)	-0.001 (-0.01; 0.009)	0.004 (-0.005; 0.01)	0.004 (-0.005; 0.01)
Proximity to the nearest green space (km)			
Averaged exposure			
FVC (L)	-0.003 (-0.01; 0.006)	-0.006 (-0.01; 0.004)	-0.006 (-0.02; 0.003)
FEV ₁ (L)	-0.002 (-0.009; 0.006)	-0.004 (-0.01; 0.003)	-0.005 (-0.01; 0.003)
FEF _{25%-75%} (L/s)	0.004 (-0.003; 0.01)	-0.004 (-0.01; 0.003)	-0.004 (-0.01; 0.002)
Early life exposure			
FVC (L)	-0.003 (-0.01; 0.007)	-0.005 (-0.01; 0.004)	-0.006 (-0.01; 0.004)
FEV ₁ (L)	-0.001 (-0.009; 0.006)	-0.004 (-0.01; 0.003)	-0.004 (-0.01; 0.003)
FEF _{25%-75%} (L/s)	0.005 (-0.003; 0.01)	-0.003 (-0.01; 0.003)	-0.004 (-0.01; 0.003)
Exposure trend over time			
FVC (L)	-0.005 (-0.01; 0.005)	-0.004 (-0.01; 0.005)	-0.003 (-0.01; 0.006)
FEV ₁ (L)	-0.004 (-0.01; 0.004)	-0.003 (-0.01; 0.004)	-0.002 (-0.01; 0.005)
FEF _{25%-75%} (L/s)	-0.003 (-0.01; 0.005)	-0.002 (-0.008; 0.004)	-0.002 (-0.008; 0.004)
Proximity to the nearest blue spaces (km)			
Averaged exposure			
FVC (L)	-0.003 (-0.01; 0.007)	0.0002 (-0.009; 0.009)	-0.0002 (-0.009; 0.009)
FEV ₁ (L)	-0.002 (-0.009; 0.006)	0.0004 (-0.007; 0.008)	-0.00007 (-0.007; 0.007)

FEF _{25%-75%} (L/s)	0.001 (-0.006; 0.009)	0.0004 (-0.006; 0.007)	0.0002 (-0.006; 0.006)
Early life exposure			
FVC (L)	-0.002 (-0.01; 0.007)	0.0007 (-0.008; 0.01)	0.0003 (-0.009; 0.009)
FEV ₁ (L)	-0.001 (-0.009; 0.006)	0.0008 (-0.006; 0.008)	0.0004 (-0.007; 0.008)
FEF _{25%-75%} (L/s)	0.002 (-0.006; 0.009)	0.0009 (-0.005; 0.007)	0.0006 (-0.006; 0.007)
Exposure trend over time			
FVC (L)	-0.003 (-0.01; 0.007)	-0.003 (-0.01; 0.006)	-0.003 (-0.01; 0.006)
FEV ₁ (L)	-0.002 (-0.01; 0.005)	-0.003 (-0.01; 0.005)	-0.002 (-0.01; 0.005)
FEF _{25%-75%} (L/s)	-0.001 (-0.009; 0.006)	-0.002 (-0.009; 0.004)	-0.002 (-0.008; 0.004)

NDVI: Normalized difference vegetation index; FVC: forced vital capacity; FEV₁: forced expiratory volume at the first second; FEF_{25%-75%}: forced expiratory flow between 25% and 75% of the FVC.

*model 1: adjusted for sex, age in months, maternal education, household monthly income, population density, and neighbourhood socioeconomic deprivation; model 2: adjusted for sex, age in months, change of residence's address, maternal education, household monthly income, population density, and neighbourhood socioeconomic deprivation; bold denotes statistically significant associations ($p < 0.05$).

TABLE S3 Associations (β , 95%CI) between the NDVI, proximity, accessibility, and number of urban green spaces and proximity to blue spaces and lung function parameters at 10 years of age adjusted for birthweight (Generation XXI, n=3278)

	[β (95%CI)]		
	Crude model	Adjusted model (1)*	Adjusted model (2)*
NDVI within 100 m			
Averaged exposure			
FVC (L)	0.01 (-0.002; 0.02)	0.003 (-0.01; 0.02)	0.003 (-0.01; 0.02)
FEV ₁ (L)	0.003 (-0.005; 0.01)	-0.002 (-0.01; 0.006)	-0.002 (-0.01; 0.006)
FEF _{25%-75%} (L/s)	0.005 (-0.002; 0.01)	-0.002 (-0.008; 0.005)	-0.002 (-0.009; 0.005)
Early life exposure			
FVC (L)	0.02 (0.003; 0.03)	0.01 (-0.006; 0.03)	0.01 (-0.006; 0.03)
FEV ₁ (L)	0.02 (0.007; 0.03)	0.01 (-0.002; 0.003)	0.01 (-0.002; 0.002)
FEF _{25%-75%} (L/s)	0.02 (0.004; 0.05)	0.02 (-0.009; 0.04)	0.02 (-0.009; 0.04)
Exposure trend over time			
FVC (L)	0.02 (0.002; 0.03)	0.01 (-0.003; 0.03)	0.01 (-0.002; 0.03)
FEV ₁ (L)	0.02 (0.004; 0.03)	0.01 (0.0002; 0.03)	0.01 (0.0003; 0.03)
FEF _{25%-75%} (L/s)	0.03 (0.004; 0.05)	0.02 (0.001; 0.05)	0.02 (0.001; 0.05)
Accessibility to green spaces within 400 m			
Averaged exposure			
FVC (L)	-0.002 (-0.03; 0.02)	-0.006 (-0.03; 0.02)	-0.006 (-0.03; 0.02)
FEV ₁ (L)	-0.004 (-0.02; 0.02)	-0.005 (-0.02; 0.01)	-0.005 (-0.02; 0.01)
FEF _{25%-75%} (L/s)	-0.02 (-0.04; 0.0004)	-0.004 (-0.02; 0.01)	-0.004 (-0.02; 0.01)
Early life exposure			
FVC (L)	-0.004 (-0.01; 0.006)	-0.007 (-0.02; 0.002)	-0.007 (-0.02; 0.002)
FEV ₁ (L)	-0.005 (-0.01; 0.003)	-0.005 (-0.01; 0.002)	-0.005 (-0.01; 0.002)
FEF _{25%-75%} (L/s)	-0.01 (-0.02; -0.003)	-0.005 (-0.01; 0.002)	-0.005 (-0.01; 0.002)

Exposure trend over			
time			
FVC (L)	0.003 (-0.007; 0.01)	0.004 (-0.005; 0.01)	0.003 (-0.006; 0.01)
FEV ₁ (L)	0.002 (-0.006; 0.009)	0.003 (-0.004; 0.01)	0.003 (-0.005; 0.01)
FEF _{25%-75%} (L/s)	-0.001 (-0.009; 0.006)	0.002 (-0.004; 0.009)	0.002 (-0.004; 0.008)
No. of green spaces			
within 400 m			
Averaged exposure			
FVC (L)	-0.002 (-0.02; 0.02)	-0.0009 (-0.02; 0.02)	-0.002 (-0.02; 0.02)
FEV ₁ (L)	-0.002 (-0.02; 0.01)	-0.0006 (-0.01; 0.01)	-0.001 (-0.01; 0.01)
FEF _{25%-75%} (L/s)	0.002 (-0.01; 0.02)	-0.0001 (-0.01; 0.01)	-0.0006 (-0.01; 0.01)
Early life exposure			
FVC (L)	-0.004 (-0.02; 0.02)	-0.002 (-0.02; 0.01)	-0.003 (-0.02; 0.01)
FEV ₁ (L)	-0.002 (-0.02; 0.01)	-0.002 (-0.02; 0.01)	-0.002 (-0.02; 0.01)
FEF _{25%-75%} (L/s)	0.002 (-0.01; 0.02)	-0.001 (-0.01; 0.01)	-0.001 (-0.01; 0.01)
Exposure trend over			
time			
FVC (L)	-0.004 (-0.02; 0.01)	-0.005 (-0.02; 0.01)	-0.004 (-0.02; 0.01)
FEV ₁ (L)	-0.003 (-0.02; 0.01)	-0.004 (-0.02; 0.02)	-0.003 (-0.02; 0.01)
FEF _{25%-75%} (L/s)	-0.003 (-0.02; 0.01)	-0.005 (-0.02; 0.007)	-0.004 (-0.02; 0.008)
Accessibility to green			
spaces within 800 m			
Averaged exposure			
FVC (L)	0.007 (-0.01; 0.03)	0.008 (-0.01; 0.03)	0.007 (-0.01; 0.03)
FEV ₁ (L)	0.004 (-0.01; 0.02)	0.006 (-0.009; 0.02)	0.006 (-0.009; 0.02)
FEF _{25%-75%} (L/s)	-0.003 (-0.02; 0.01)	0.005 (-0.007; 0.02)	0.005 (-0.007; 0.02)
Early life exposure			
FVC (L)	-0.0004 (-0.01; 0.01)	0.0005 (-0.009; 0.01)	0.0003 (-0.009; 0.009)

FEV ₁ (L)	-0.002 (-0.02; 0.01)	0.0003 (-0.007; 0.008)	0.0002 (-0.007; 0.007)
FEF _{25%-75%} (L/s)	-0.005 (-0.01; 0.002)	0.0005 (-0.006; 0.007)	0.0003 (-0.006; 0.007)
Exposure trend over time			
FVC (L)	-0.004 (-0.01; 0.004)	-0.0003 (-0.008; 0.007)	-0.0005 (-0.009; 0.008)
FEV ₁ (L)	-0.003 (-0.01; 0.03)	-0.0003 (-0.006; 0.006)	-0.0005 (-0.008; 0.007)
FEF _{25%-75%} (L/s)	-0.005 (-0.008; 0.004)	-0.007 (-0.006; 0.005)	-0.0009 (-0.007; 0.005)
No. of green spaces within 800 m			
Averaged exposure			
FVC (L)	-0.007 (-0.02; 0.009)	-0.001 (-0.02; 0.01)	-0.002 (-0.02; 0.01)
FEV ₁ (L)	-0.005 (-0.02; 0.007)	-0.001 (-0.01; 0.01)	-0.002 (-0.01; 0.01)
FEF _{25%-75%} (L/s)	-0.005 (-0.02; 0.006)	-0.002 (-0.01; 0.008)	-0.002 (-0.01; 0.008)
Early life exposure			
FVC (L)	-0.006 (-0.02; 0.008)	-0.002 (-0.01; 0.01)	-0.002 (-0.01; 0.01)
FEV ₁ (L)	-0.005 (-0.02; 0.006)	-0.001 (-0.01; 0.009)	-0.002 (-0.01; 0.008)
FEF _{25%-75%} (L/s)	-0.005 (-0.01; 0.005)	-0.002 (-0.01; 0.007)	-0.002 (-0.01; 0.006)
Exposure trend over time			
FVC (L)	0.002 (-0.01; 0.01)	0.007 (-0.006; 0.02)	0.007 (-0.006; 0.02)
FEV ₁ (L)	0.0008 (-0.01; 0.01)	0.005 (-0.005; 0.02)	0.005 (-0.004; 0.02)
FEF _{25%-75%} (L/s)	-0.001 (-0.01; 0.009)	0.004 (-0.005; 0.01)	0.004 (-0.005; 0.01)
Distance to the nearest green space (km)			
Averaged exposure			
FVC (L)	-0.003 (-0.01; 0.006)	-0.006 (-0.01; 0.004)	-0.005 (-0.01; 0.004)
FEV ₁ (L)	-0.002 (-0.009; 0.006)	-0.004 (-0.01; 0.003)	-0.004 (-0.01; 0.003)
FEF _{25%-75%} (L/s)	0.004 (-0.003; 0.01)	-0.004 (-0.01; 0.003)	-0.003 (-0.01; 0.003)

Early life exposure			
FVC (L)	-0.003 (-0.01; 0.007)	-0.005 (-0.01; 0.004)	-0.005 (-0.01; 0.004)
FEV ₁ (L)	-0.001 (-0.009; 0.006)	-0.004 (-0.01; 0.003)	-0.004 (-0.01; 0.004)
FEF _{25%-75%} (L/s)	0.005 (-0.003; 0.01)	-0.003 (-0.01; 0.003)	-0.003 (-0.01; 0.003)
Exposure trend over time			
FVC (L)	-0.005 (-0.01; 0.005)	-0.004 (-0.01; 0.005)	-0.003 (-0.01; 0.006)
FEV ₁ (L)	-0.004 (-0.01; 0.004)	-0.003 (-0.01; 0.004)	-0.003 (-0.01; 0.005)
FEF _{25%-75%} (L/s)	-0.003 (-0.01; 0.005)	-0.002 (-0.008; 0.004)	-0.002 (-0.008; 0.004)
Distance to the nearest blue spaces (km)			
Averaged exposure			
FVC (L)	-0.003 (-0.01; 0.007)	0.0002 (-0.009; 0.009)	-0.0003 (-0.009; 0.009)
FEV ₁ (L)	-0.002 (-0.009; 0.006)	0.0004 (-0.007; 0.008)	-0.00004 (-0.007; 0.007)
FEF _{25%-75%} (L/s)	0.001 (-0.006; 0.009)	0.0004 (-0.006; 0.007)	0.00008 (-0.006; 0.006)
Early life exposure			
FVC (L)	-0.002 (-0.01; 0.007)	0.0007 (-0.008; 0.01)	0.0002 (-0.009; 0.01)
FEV ₁ (L)	-0.001 (-0.009; 0.006)	0.0008 (-0.006; 0.008)	0.0004 (-0.007; 0.008)
FEF _{25%-75%} (L/s)	0.002 (-0.006; 0.009)	0.0009 (-0.005; 0.007)	0.0005 (-0.006; 0.007)
Exposure trend over time			
FVC (L)	-0.003 (-0.01; 0.007)	-0.003 (-0.01; 0.006)	-0.003 (-0.01; 0.006)
FEV ₁ (L)	-0.002 (-0.01; 0.005)	-0.003 (-0.01; 0.005)	-0.002 (-0.01; 0.005)
FEF _{25%-75%} (L/s)	-0.001 (-0.009; 0.006)	-0.002 (-0.009; 0.004)	-0.002 (-0.009; 0.004)

NDVI: Normalized difference vegetation index; FVC: forced vital capacity; FEV₁: forced expiratory volume at the first second; FEF_{25%-75%}: forced expiratory flow between 25% and 75% of the FVC.

*model 1: adjusted for sex, age in months, maternal education, household monthly income, population density, and neighbourhood socioeconomic deprivation; model 2: adjusted for sex, age in months, low birth weight, maternal

education, household monthly income, population density, and neighbourhood socioeconomic deprivation; bold denotes statistically significant associations ($p < 0.05$).

TABLE S4 Associations (β , 95%CI) between the existence of green spaces and lung function parameters at 10 years of age (Generation XXI, n=3278) [4 times access to UGS vs. 1 time access to UGS from birth to 10 years of age][†]

	[β (95%CI)]	
	Crude model	Adjusted model*
Green spaces within 400 m		
Averaged exposure		
FVC (L)	-0.008 (-0.04; 0.02)	-0.009 (-0.04; 0.02)
FEV ₁ (L)	-0.01 (-0.03; 0.01)	-0.007 (-0.03; 0.02)
FEF _{25%-75%} (L/s)	-0.03 (-0.05; -0.008)	-0.007 (-0.03; 0.01)
Early life exposure		
FVC (L)	-0.004 (-0.01; 0.006)	-0.007 (-0.02; 0.002)
FEV ₁ (L)	-0.005 (-0.01; 0.003)	-0.005 (-0.01; 0.002)
FEF _{25%-75%} (L/s)	-0.01 (-0.02; -0.003)	-0.005 (-0.01; 0.002)
Exposure trend over time		
FVC (L)	0.003 (-0.007; 0.01)	0.004 (-0.005; 0.01)
FEV ₁ (L)	0.002 (-0.006; 0.009)	0.003 (-0.004; 0.01)
FEF _{25%-75%} (L/s)	-0.001 (-0.009; 0.006)	0.002 (-0.004; 0.009)
Green spaces within 800 m		
Averaged exposure		
FVC (L)	-0.002 (-0.02; 0.02)	0.002 (-0.02; 0.02)
FEV ₁ (L)	-0.003 (-0.02; 0.01)	0.002 (-0.01; 0.02)
FEF _{25%-75%} (L/s)	-0.01 (-0.03; 0.002)	0.002 (-0.01; 0.02)
Early life exposure		
FVC (L)	-0.0004 (-0.01; 0.01)	0.0005 (-0.009; 0.01)
FEV ₁ (L)	-0.002 (-0.02; 0.01)	0.0003 (-0.007; 0.008)
FEF _{25%-75%} (L/s)	-0.005 (-0.01; 0.002)	0.0005 (-0.006; 0.007)

Exposure trend over time		
FVC (L)	-0.004 (-0.01; 0.004)	-0.0003 (-0.008; 0.007)
FEV ₁ (L)	-0.003 (-0.01; 0.03)	-0.0003 (-0.006; 0.006)
FEF _{25%-75%} (L/s)	-0.005 (-0.008; 0.004)	-0.007 (-0.006; 0.005)

NDVI: Normalized difference vegetation index; FVC: forced vital capacity; FEV₁: forced expiratory volume at the first second; FEF_{25%-75%}: forced expiratory flow between 25% and 75% of the FVC.

[†]children who had access to UGS in all the cohort evaluations (4 times from birth to 10 years of age) from those who had access to one of the cohort evaluations (1 time).

*adjusted for sex, age in months, maternal education, household monthly income, population density, and neighbourhood socioeconomic deprivation.

TABLE S5 Characteristics of participants included and excluded (Generation XXI, n=3278)

	Participants included	Participants excluded	p value
Characteristics	n (%)	n (%)	
<i>At birth</i>			
Sex [female, n (%)]	1654 (50.5)	2756 (51.3)	0.312
Maternal education			<0.05
Primary (≤9 years)	1372 (41.9)	2877 (53.7)	
Secondary (10–12 years)	962 (29.3)	1352 (25.2)	
Tertiary (>12 years)	944 (28.8)	1129 (21.1)	
Household monthly income (€)			<0.05
≤ 1000	1060 (34.7)	2080 (44.4)	
1001-1500	895 (29.3)	1275 (27.2)	
> 1500	1101 (36.0)	1327 (28.3)	
Neighbourhood socioeconomic deprivation			<0.05
Q1 (least deprived)	460 (14.0)	645 (12.1)	
Q2	712 (21.7)	969 (18.2)	
Q3	809 (24.7)	1329 (24.9)	
Q4	744 (22.7)	1180 (22.1)	
Q5 (most deprived)	553 (16.9)	1213 (22.7)	
<i>At 10 years</i>			
Physically active [yes]	2079 (63.5)	1839 (59.0)	0.019

TABLE S6 Missing data (Generation XXI, n=3278)

Characteristic	n (%)
<i>At birth</i>	
NDVI	0 (0)
Accessibility to green spaces within 400 m (yes)	0 (0)
No. of green spaces within 400 m*	0 (0)
Accessibility to green spaces within 800 m (yes)	0 (0)
No. of green spaces within 800 m*	0 (0)
Distance to the nearest green space (km)	0 (0)
Distance to the nearest blue spaces (km)	0 (0)
Sex [female, n (%)]	0 (0)
Maternal education	0 (0)
Household monthly income (€)	222 (6.8)
Neighbourhood socioeconomic deprivation**	0 (0)
<i>At 4 years</i>	
NDVI	
100 m	27 (0.8)
250 m	3 (0.1)
500 m	0 (0)
Accessibility to green spaces within 400 m (yes)	0 (0)
No. of green spaces within 400 m*	0 (0)
Accessibility to green spaces within 800 m (yes)	0 (0)
No. of green spaces within 800 m*	0 (0)
Distance to the nearest green space (km)	0 (0)
Distance to the nearest blue spaces (km)	0 (0)
<i>At 7 years</i>	
NDVI	0 (0)
Accessibility to green spaces within 400 m (yes)	0 (0)

No. of green spaces within 400 m*	0 (0)
Accessibility to green spaces within 800 m (yes)	0 (0)
No. of green spaces within 800 m*	0 (0)
Distance to the nearest green space (km)	0 (0)
Distance to the nearest blue spaces (km)	0 (0)
<i>At 10 years</i>	
BMI (kg/m ²)*	4 (0.1)
Physically active [yes]	5 (0.2)
FVC before bronchodilation (L)**	0 (0)
FEV ₁ before bronchodilation (L)**	0 (0)
FEF _{25%-75%} before bronchodilation (L/s)**	0 (0)
Outdoor levels of NO ₂ (µg/m ³)*	0 (0)
NDVI	0 (0)
Accessibility to green spaces within 400 m (yes)	0 (0)
No. of green spaces within 400 m*	0 (0)
Accessibility to green spaces within 800 m (yes)	0 (0)
No. of green spaces within 800 m*	0 (0)
Distance to the nearest green space (km)	0 (0)
Distance to the nearest blue spaces (km)	0 (0)

NDVI: Normalized difference vegetation index; FVC: forced vital capacity; FEV₁: forced expiratory volume at the first second; FEF_{25%-75%}: forced expiratory flow between 25% and 75% of the FVC; NO₂: nitrogen dioxide

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4.3. Surrounding greenness and behavioural problems in the Generation XXI cohort: a life course approach.

Almeida, D. Q., Barros, H., Ribeiro, A. I., “Surrounding greenness and behavioural problems in the Generation XXI cohort: a life course approach.” (submitted)

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Surrounding greenness and behavioural problems in the Generation XXI cohort: a life course approach.

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Corresponding Author:	Diogo Queiroz Almeida ISPUP EPIUnit Porto, PORTUGAL
First Author:	Diogo Queiroz Almeida
Order of Authors:	Diogo Queiroz Almeida Henrique Barros Ana Isabel Ribeiro
Abstract:	Behaviour in children is influenced by a complex interplay of genetic, social, and environmental factors. While studies have shown beneficial effects of greenness in mitigating behavioural issues such as hyperactivity and inattention, knowledge gaps remain regarding the impact of specific vegetation types, exposure timing, and potential mediators such as physical activity, sleep, maternal mental health, and air pollution. The study used data from the Generation XXI, a population-based birth cohort from the Porto Metropolitan Area (Portugal). Greenness was assessed using the Normalized Difference Vegetation Index (NDVI) and percentage of tree coverage area, percentage of non-tree vegetation area, and the mean percentage of non-vegetated area within 100-, 250-, and 500-meter buffers around children's residences at birth, 4, and 7 years of age. Three life course measures were calculated: averaged exposure, early life exposure (birth) and exposure trend over time (change in exposure). Behavioural problems were reported by caregivers. The analyses were adjusted for different confounders, namely maternal education, household income, population density, and socioeconomic deprivation. Potential mediators – physical activity, air pollution (PM2.5 and NO2), sleep duration, and maternal mental health – were evaluated using structural equation modeling. Results showed that higher exposure to greenness, particularly non-tree vegetation and averaged NDVI within 250- and 500-meter buffers, was consistently associated with a lower prevalence of reported behavioural problems. Conversely, higher exposure to non-vegetated areas was linked to increased reports of behavioural problems. The findings emphasize that increasing accessible, well-designed greenspaces could serve as a public health strategy to promote children's behavioural well-being.

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Dear Editor,

Please find enclosed a research manuscript entitled “Residential greenness exposure and behavioural problems in children: a life-course approach in the Generation XXI birth cohort” by Diogo Queiroz Almeida, Henrique Barros, and Ana Isabel Ribeiro for consideration for publication in Science of the Total Environment.

Behavioural problems in children are a significant public health concern, with long-term implications for education, social functioning, and health. While previous studies have suggested beneficial effects of green space exposure on child development, important knowledge gaps remain regarding the role of specific vegetation types, critical windows of exposure, and potential mediating pathways.

In this study, we used longitudinal data from the Generation XXI birth cohort in Porto, Portugal, including 6,269 children, to examine the association between different measures of residential greenness, captured at birth, ages 4 and 7, and using a life-course approach, and the prevalence of behavioural problems reported at age 7. Exposure was assessed through NDVI, tree cover, non-tree vegetation, and non-vegetated areas, within multiple residential buffers. We further investigated the potential mediating role of physical activity, sleep, maternal mental health, and air pollution.

We found that higher exposure to greenness, particularly non-tree vegetation and averaged NDVI within 250 m and 500 m, was consistently associated with lower prevalence of behavioural problems, while higher exposure to non-vegetated areas was associated with an increased prevalence. These findings highlight the relevance of early-life and sustained exposure to green spaces for children’s behavioural well-being and provide valuable evidence to support urban planning policies aimed at improving child health through the provision of accessible and well-designed green environments.

All authors have read and agreed to the contents of the manuscript and approved its submission to Science of the Total Environment. We certify that the manuscript, or any part of it, has neither been published nor is currently under consideration for publication in any other journal.

Yours faithfully,
Diogo Queiroz Almeida
on behalf of the co-authors

Article title

Surrounding greenness and behavioural problems in the Generation XXI cohort: a life course approach.

Authors' full names (without degrees) and affiliations at the time the work was done

Diogo Queiroz Almeida^{a,b}, Henrique Barros^a, Ana Isabel Ribeiro^{a,b,c}

^aEPIUnit ITR, Instituto de Saúde Pública da Universidade do Porto, Universidade do Porto, Rua das Taipas, n° 135, 4050-600 Porto, Portugal

^bDepartamento de Ciências da Saúde Pública e Forenses e Educação Médica, Faculdade de Medicina, Universidade do Porto, Alameda Prof. Hernâni Monteiro, 4200-319 Porto, Portugal

^cDepartamento de Geografia, Faculdade de Letras da Universidade do Porto, Centro de Estudos em Geografia e Ordenamento do Território (CEGOT), Via Panorâmica, s/n, 4150-564 Porto, Portugal

Corresponding author's name and mailing address, telephone number, and e-mail address

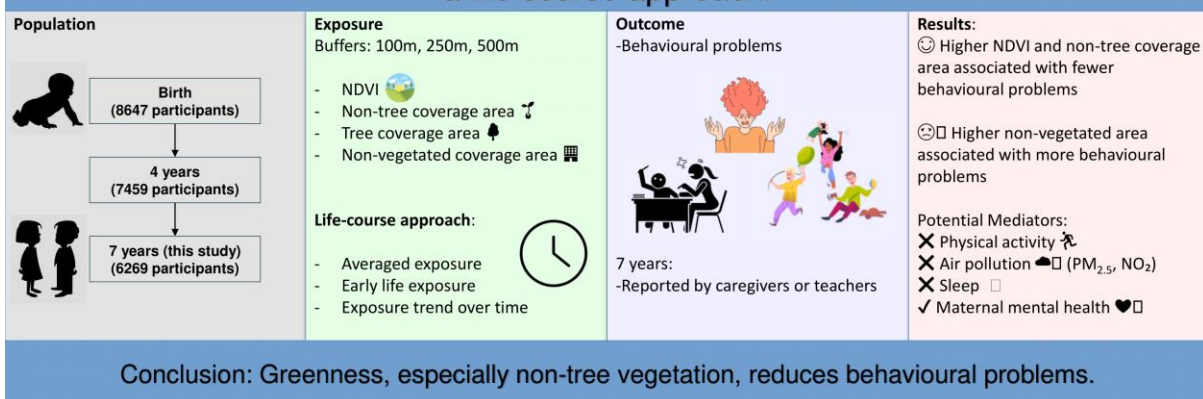
Diogo Queiroz Almeida

Rua das Taipas, n° 135, 4050-600 Porto, Portugal.

+351 960487479

diogo.queiroz.almeida@gmail.com

Surrounding greenness and behavioural problems in the Generation XXI cohort: a life course approach.



Highlights [3 to 5 bullet points, each with a maximum of 85 characters, including spaces]

- Higher greenness is associated with less behavioural problems in children.
- Non-tree vegetation showed a stronger protective effect compared to tree coverage.
- There is a need for well-designed greenspaces to support child development.

[Click here to view linked References](#)

1 **Abstract**

2 Behaviour in children is influenced by a complex interplay of genetic, social, and environmental
3 factors. While studies have shown beneficial effects of greenness in mitigating behavioural issues
4 such as hyperactivity and inattention, knowledge gaps remain regarding the impact of specific
5 vegetation types, exposure timing, and potential mediators such as physical activity, sleep,
6 maternal mental health, and air pollution.

7 The study used data from the Generation XXI, a population-based birth cohort from the Porto
8 Metropolitan Area (Portugal). Greenness was assessed using the Normalized Difference
9 Vegetation Index (NDVI) and percentage of tree coverage area, percentage of non-tree vegetation
10 area, and the mean percentage of non-vegetated area within 100-, 250-, and 500-meter buffers
11 around children's residences at birth, 4, and 7 years of age. Three life course measures were
12 calculated: averaged exposure, early life exposure (birth) and exposure trend over time (change
13 in exposure). Behavioural problems were reported by caregivers. The analyses were adjusted for
14 different confounders, namely maternal education, household income, population density, and
15 socioeconomic deprivation. Potential mediators – physical activity, air pollution (PM_{2.5} and NO₂),
16 sleep duration, and maternal mental health – were evaluated using structural equation modeling.

17 Results showed that higher exposure to greenness, particularly non-tree vegetation and averaged
18 NDVI within 250- and 500-meter buffers, was consistently associated with a lower prevalence of
19 reported behavioural problems. Conversely, higher exposure to non-vegetated areas was linked
20 to increased reports of behavioural problems.

21 The findings emphasize that increasing accessible, well-designed greenspaces could serve as a
22 public health strategy to promote children's behavioural well-being.

23

24 **Keywords**

25 behavioural problems, green space exposure, child development

1. Introduction

Behavioural problems in children are relatively common and reflect the child's social stressors, environment and developmental state. Behavioural problems affect between 9.4% and 9.8% of children aged 3 and adolescents with 17 in the USA [1], and between 17.4% and 17.9% of children aged 6 and adolescents with 16 in China [2]. Behavioural problems in children can be divided into externalising problems such as aggression, oppositional behaviour and hyperactivity, and internalising problems such as anxiety and depression [3]. Behavior development is multifactorial, and is affect by genetics [4], but also by environmental factors, such as socialization with the caretakers (usually the parents) [5], and the peers [6]. As such, the aetiology of behavioral problems, is multifaceted, influenced by social stressors, environmental factors, developmental stages, biological vulnerabilities, and environmental stressors [7].

Behavioural problems among children represent a major public health and educational concern [8]. Early identification and intervention are critical as they can significantly impact a child's academic performance in the short term [9] but also in the long term, namely in the consumption of tobacco and drugs, as well as riskier sexual behaviours [10].

In recent years, attention has turned to the impact of environmental factors, particularly the presence of green spaces, on children's behavioral development. A systematic review from 2022 [11] evaluated available evidence until November 2021, found that green spaces have a beneficial influence in terms of behaviour problems – behavioural difficulties, attention deficit hyperactivity disorder (ADHD) symptom and severity, conduct problems, ADHD diagnosis, prosocial behavior, emotional symptoms, peer-relationship problems, externalizing disorders and internalizing disorders. Likewise, a review by Zhang et al. [12] documented a beneficial impact of green space exposure on children's emotional and behavioral well-being, particularly in mitigating hyperactivity and inattention problems. In [13], it was found that larger distances from the residence to nearest urban green space was associated with higher odds of hyperactivity and inattention. A study specifically focused on ADHD, revealed that the exposure to greenness measured by the Normalized Difference Vegetation Index (NDVI) for buffers of 250 meters and

53 500 meters has been inversely associated with the use of medication for ADHD in children
54 between 5 and 12 years [14]. Pointing in the same direction, the practice of different activities in
55 green settings was found to be superior at reducing the symptoms of ADHD in children between
56 5 and 18 years of age when compared with activities done in urban outdoors and indoors [15].

57 Exposure to green spaces can have a protective effect on the development and management of
58 behavioral problems in children by different mechanisms: physical activity, pollution reduction,
59 better sleep, and improvement of parents' mental health [16]. Physical activity benefits children
60 and adolescents with ADHD [17], possibly due to promoting an increase in dopamine,
61 norepinephrine, and serotonin. Air pollution (both particulate and gaseous) can have an
62 association with behavioural problems (although still not consensual) [18], with different
63 mechanisms having been proposed, namely increased oxidative stress, neuroinflammation, or
64 endocrine disruption. Sleep disturbance is an internal stressor, which has been associated with
65 behavioral problems in children [19] since sleep disruption can lead to compromised
66 neurobehavioral functioning [20]. The parent's mental health is also a source of stress for
67 children, which can be associated with behavioural problems since parents' poor mental health
68 can lead to inadequate care and, consequently, emotional trauma [21].

69 The rationale for this study stems from identified gaps in existing literature. Regarding exposure,
70 while several studies have already assessed the association between residential greenness, as
71 measured by NDVI [13] and land cover [22], and behavioural problems, the influence of diverse
72 vegetation types, including tree coverage, remains unexamined. This is relevant because the kind
73 of behaviours and benefits that can emerge from different types of vegetation can differ.
74 Furthermore, most studies assessed the exposure using a cross-sectional design, focusing on
75 simultaneous assessment of exposure and outcome simultaneously, with only a few considering
76 exposures at birth [11]. The studies with a longitudinal design used the average exposure [23] and
77 did not consider other relevant measures, namely the exposure at birth or the evolution of the
78 exposure, which can shed light on the existence of critical periods of exposure [24]. Regarding
79 the possible mechanisms by which green spaces can have a beneficial effect on the control of

80 behavioural problems in children little is known. The role of physical activity as a mediator in the
81 association between green spaces and behavioural problems was studied elsewhere [25], and
82 although physical activity was identified as a mediator, it only partially explained the observed
83 effect. However, as previously shown, other possible mediators, namely air pollution [18], sleep
84 [19] and mother's mental health [21], both influenced by green space [16], can affect the existence
85 of behavioural problems in children.

86 Building on this framework, this study aimed to assess the association between exposure to
87 greenness—measured using various exposure metrics within a comprehensive life course
88 approach—and behavioral problems reported at 7 years of age. The study also explored potential
89 mediators, including physical activity, air pollution, sleep duration, and maternal mental health.

90

91

92

93

94 2. Methods

95

96 2.1 Study participants

97

98 This study was conducted in the Porto Metropolitan Area, which is constituted by a cluster of
99 cities located in the north-west of Portugal.

100 The study uses data from the Generation XXI birth cohort (G21)
101 (<https://www.geracao21.com/en/>), a population-based birth cohort that recruited 8495 mothers
102 and 8647 newborns (wave 1) from five public maternities of the Porto Metropolitan area (where
103 95% of the region's births happen), between April 2005 and September 2006. Of the eligible
104 newborns, 91.4% of the legal representatives allowed them to participate [26]. The participants
105 were re-evaluated at ages four (wave 2, n=7459), seven (wave 3, n=6889), ten (wave 4, n=6392),
106 thirteen (wave 5, n=4643, an evaluation that was interrupted due to the restrictive social measures
107 implemented in response to the Covid-19 pandemic), and at eighteen (wave 6, ongoing). In this
108 study, we used data from wave 3. Ethical approval for the G21 was obtained from the Ethics
109 Committee of the Faculdade de Medicina da Universidade do Porto/Hospital de São João (CES-
110 01/2017) and by the National Committee of Data Protection, and signed informed consent was
111 obtained from all participants' legal representatives in every evaluation. All the phases of the G21
112 complied with the Ethical Principles for Medical Research Involving Human Subjects expressed
113 in the Declaration of Helsinki.

114 Children's residential address was collected during routine telephone calls with the caregiver (in
115 each evaluation). Residential addresses were processed and georeferenced using ArcGIS Online
116 World Geocoding Service and Google Earth under strict geoprivacy-conserving guidelines [27].
117 For the present study, we included children living in Porto Metropolitan Area at 7 years of age
118 and with data regarding behavioral problems, totaling 6269 children (Figure 1).

119 INSERT FIGURE 1

120 Figure 1 – Flowchart of the participants of the cohort.

121

122 **2.2 Health outcome**

123 Behavioral problems were assessed in the G21 at the age of 7, through a structured questionnaire
124 filled by the legal representatives. The questionnaire included a section in which respondents were
125 asked whether they, or the child's teacher, had ever suspected the child to have problems in
126 various domains, including learning, attention, language, socialization, and behavioral problems
127 (defined in the questionnaire as "impulsivity, hyperactivity, aggressiveness"). The response was
128 binary. When "Yes" was selected, respondents were further asked whether the child had received
129 a clinical diagnosis.

130

131 **2.3 Exposure assessment**

132 Greenness was assessed based on different measures. We used the mean Normalized Difference
133 Vegetation Index (NDVI) within 100, 250 and 500 meters of the residence of the participants at
134 0, 4 and 7 years of age. These buffer sizes were defined to capture different possible mechanisms
135 of greenness [16] and were employed in other studies from G21 [28-30]. NDVI was calculated
136 based on land reflection of the electromagnetic waves in the spectrum of visible light and near-
137 infrared wavelengths. Values can range between -1 (water) and 1, with more positive values
138 indicating denser green vegetation. Negative NDVI values were omitted from the calculation.
139 Images with less than 5% of nebulosity from the Landsat 5 and 8 missions (spatial resolution: 30
140 m) from the spring/summer period (peak of vegetation) of the assessment years (2005/6, 2009/11,
141 2012/14) were used, as previously described in other G21 studies [28-30].

142 Additionally, we also assessed the mean percentage of tree coverage (measured as light
143 penetration to the ground compared to "crown" cover), the mean percentage of non-tree
144 vegetation area (measured in a similar fashion to tree canopy cover), and the mean percentage of
145 non-vegetated area (100% - mean percentage of tree coverage - mean percentage of non-tree

146 vegetation area) within 100, 250 and 500 meters of the residence of the participants at 0, 4 and 7
147 years of age. For that, we used images from Moderate Resolution Imaging Spectroradiometer
148 (MODIS) Vegetation Continuous Fields (spatial resolution: 250 m) [31].

149 The correlation matrix between the greenness exposures variables can be assessed in Figure A
150 (100 meters), Figure B (250 meters), and Figure C (500 meters) of the supplementary material.
151 Most values exhibited moderate correlations with one another.

152 ArcMap 10.5 was used to process satellite images, and QGIS 3.8 was used to the average levels
153 of exposure in the home surroundings.

154

155 **2.4 Covariates**

156 The following variables were included: sex (categorical), maternal educational level (categorical),
157 household monthly income (categorical), population density (numerical), and neighbourhood
158 socioeconomic deprivation (numerical). The choice of covariates was theory-driven [32] based
159 on the published literature on related topics [29, 33]. Maternal educational level was measured in
160 years of schooling and categorized into three classes: International Standard Classification of
161 Education 2011 (ISCED) 0 to 2 - primary; ISCED 3 - secondary; and ISCED 4 to 6 - tertiary.
162 Household monthly income was categorized into three groups: ≤ 1000 euros, 1001–1500 euros
163 and > 1500 euros. Population density at the neighbourhood level was obtained from the Statistics
164 Portugal (for the year 2011) [34]. Neighbourhood socioeconomic deprivation at age 7 was
165 measured using the European Deprivation Index with lower values corresponding to least
166 deprived areas [35].

167 Mediation analyses were then performed for four mediators, measured at age seven: physical
168 activity, air pollution, sleep, and mother's mental health. The practice of physical activity was
169 defined as an engagement in physical exercise and active leisure activities performed on a
170 repeated and regular basis. Time spent (min/week) in physical activities was considered.

171 Outdoor levels of air pollution in the residence were assessed using the annual average
172 concentrations of particulate matter 2.5 (PM_{2.5}), and nitrogen dioxide (NO₂) with a 100×100
173 spatial resolution obtained from the standardised Europe-wide hybrid land-use regression models
174 [36]. These values were estimated for 2010 within the ELAPSE project and were back-
175 extrapolated using the ratio method for 2015 (the latest year for which ratios were available).

176 Hours of sleep were calculated for both the weekdays and for the weekends as the difference
177 between the wake-up time and bedtime. went to bed. The variable included was the weighted
178 average of the hours of sleep of the weekdays (with a weight of 5/7 for the five days of the week)
179 and the hours of sleep of the weekends (with a weight of 2/7 for the two days of the weekend).

180 The mental health of the mothers' participants was assessed at the evaluation of the 7 years
181 resorting to the Hospital Anxiety and Depression Scale (HADS) scale. The HADS is a self-
182 administered questionnaire developed by Zigmond and Snaith [37], and consists of fourteen
183 different items, seven related to anxiety and seven related to depression, each item with a possible
184 score ranging from 0 to 3. Scores above seven for the depression scale indicated major depression
185 [38], and eight for anxiety [39].

186

187 **2.5 Statistical analysis**

188 Three approaches were used to assess the effect of greenness at the residential level on
189 behavioural problems at 7 years of age: 1) mean exposure; 2) early life exposure; 3) exposure
190 trend over time. For the mean exposure, the exposure variables were averaged from birth to 7
191 years of age. To assess early life exposure and exposure trend over time, a linear mixed methods
192 analysis was performed, with time as the independent variable and the different exposures as the
193 dependent variables to obtain specific curves, with each participant as a grouping variable. From
194 the regression, the intercept was used as an indicator of early life exposure and the slope as the
195 trend of exposure over time. This approach has been used in another study by the team [28].

196 A logistic model was fitted to estimate the crude and adjusted associations. The adjusted models
197 included the covariates described in the previous section. Results were expressed as odds ratio
198 (OR) and 95% confidence intervals (95% CI).

199 The mediation effects of physical activity, outdoor levels of pollution (NO₂ and PM_{2.5}), hours of
200 sleep, and HADS score of the mother were assessed with structural equation modelling (SEM).
201 SEM methods are based on path analysis and test both direct and indirect effects of possible causal
202 relationships [40]. The weighted least square mean and variance adjusted estimator was used due
203 to the dichotomic nature of the outcome variable.

204 Missing data was handled resorting to Multivariate Imputation by Chained Equation. This method
205 generates multiple imputations for each missing value. A total of 20 imputations were used to
206 estimate the missing values. The distribution of missing data, along with the regression analysis,
207 is provided in the supplementary material table A to table F. This section also includes results
208 from the non-imputed datasets, which were found to be consistent with those obtained using
209 imputed data.

210 Statistical analysis was performed using R software version 3.6.2.

211

212 3. Results

213 The study participants' characteristics and the measures of the mediators are presented in Table

214 1. At the age of 7, 12.65% of participants were reported by their parents to have behavioral

215 problems.

216 Table 1 - Characteristics of participants (Generation XXI, n=6269)

Characteristic	n (%) or mean (SD)
<i>At birth</i>	
Sex [female, n (%)]	3216 (51.30%)
Maternal education	
Primary (≤ 9 years)	2683 (42.79%)
Secondary (10–12 years)	1849 (29.49%)
Tertiary (> 12 years)	1737 (27.71%)
Household monthly income (€)	
≤ 1000	1970 (31.42%)
1001-1500	1681 (26.82%)
> 1500	2618 (41.76%)
Neighbourhood socioeconomic deprivation	0.09 (2.69)
Population Density (inhabitants per km ²)	9078 (8678)
<i>At 7 years</i>	
Reported behavioural problems (yes/no)	793 (12.65%)
Physical Activity (hours/week)	3.01 (2.47)
NO ₂	27.36 (6.03)
PM _{2.5}	13.69 (1.04)
HADS of the mother	12.13 (6.53)
Sleep duration (hours)	10.21 (0.60)

217 HADS: Hospital Anxiety and Depression Scale

218 The different measures of greenness are presented in Table 2. The mean NDVI within 100 meters,

219 250 meters and 500 meters increased slightly over time. The same is true for the mean percentage

of non-tree vegetation area and the mean percentage of tree coverage area. The mean percentage of non-vegetated area has a descending trajectory.

Table 2 - Exposure to greenness in the residential neighbourhood (Generation XXI, n=6269)

Exposure variables	Mean (SD)		
	At birth	At 4 years	At 7 years
NDVI			
100 m	0.163 (0.077)	0.181 (0.073)	0.206 (0.060)
250 m	0.201 (0.075)	0.214 (0.072)	0.230 (0.059)
500 m	0.222 (0.072)	0.234 (0.069)	0.243 (0.058)
Mean percentage of non-vegetated area			
100 m	33.82 (14.84)	33.95 (14.71)	31.35 (14.17)
250 m	33.12 (14.41)	33.28 (14.26)	30.82 (13.60)
500 m	31.65 (13.45)	31.79 (13.15)	29.62 (12.39)
Mean percentage of non-tree vegetation area			
100 m	57.55 (11.04)	57.86 (11.28)	58.76 (11.11)
250 m	57.95 (10.48)	58.22 (10.65)	59.02 (10.45)
500 m	58.63 (9.28)	58.82 (9.21)	59.29 (8.99)
Mean percentage of tree coverage area			
100 m	8.63 (6.76)	8.20 (6.39)	9.89 (6.94)
250 m	8.92 (6.78)	8.50 (6.56)	10.16 (7.00)
500 m	9.72 (6.93)	9.39 (6.94)	11.09 (7.28)

Table 3 presents the crude and adjusted associations between NDVI and behavioural problems at 7 years of age. Although no statistically significant associations were observed in the crude models across the different buffers, adjusted models revealed a protective effect of higher NDVI

values at birth on behavioral problems at 7 years of age for 250-meter and 500-meter buffers. Additionally, a protective effect was observed for mean NDVI exposure across all buffer zones.

Table 3 - Associations (OR, 95%CI) between NDVI and behavioural problems at 7 years of age (Generation XXI, n=6269)

	[OR (95%CI)] reported	
	Crude model	Adjusted model*
NDVI within 100 m		
Early life exposure	0.638 (0.203, 1.97)	0.285 (0.079, 1.02)
Exposure trend over time	0.005 (0, 6.67x10 ⁶)	115.171 (0, 8.83 x10 ¹¹)
Averaged exposure	0.540 (0.164, 1.749)	0.242 (0.064, 0.907)
NDVI within 250 m		
Early life exposure	0.459 (0.150, 1.392)	0.22 (0.063, 0.753)
Exposure trend over time	0.006 (0, 5.03x10 ⁶)	12.045 (0, 3.65x10 ¹⁰)
Averaged exposure	0.36 (0.109, 1.17)	0.165 (0.044, 0.608)
NDVI within 500 m		
Early life exposure	0.441 (0.142, 1.356)	0.246 (0.071, 0.843)
Exposure trend over time	0.018 (0, 2.81x10 ⁷)	1.42 (0, 6.80x10 ⁹)
Averaged exposure	0.347 (0.103, 1.159)	0.18 (0.048, 0.676)

*adjusted for sex, maternal education, household monthly income, population density and neighbourhood socioeconomic deprivation

Table 4 presents the crude and adjusted associations between the mean percentage of non-vegetated area and behavioral problems at 7 years of age. In the crude models, higher percentages of non-vegetated area showed a deleterious effect at 250-meter and 500-meter buffers for mean exposure, as well as at 250 meters at birth. In the adjusted models, a consistent deleterious effect was observed across all buffers, both for mean exposure and at birth exposure.

Table 4 - Associations (OR, 95%CI) between mean percentage of non-vegetated area and behavioral problems at 7 years of age (Generation XXI, n=6269)

	[OR (95%CI)] reported	
	Crude model	Adjusted model*
Mean percentage of non-vegetated area within 100 m		
Early life exposure	1.005 (0.999, 1.011)	1.009 (1.003, 1.016)
Exposure trend over time	1.022 (0.909, 1.148)	0.990 (0.878, 1.116)
Averaged exposure	1.005 (0.999, 1.010)	1.009 (1.003, 1.015)
Mean percentage of non-vegetated area within 250 m		
Early life exposure	1.006 (1.000, 1.012)	1.010 (1.004, 1.017)
Exposure trend over time	1.025 (0.913, 1.15)	1.002 (0.889, 1.128)
Averaged exposure	1.006 (1.001, 1.012)	1.010 (1.004, 1.017)
Mean percentage of non-vegetated area within 500 m		
Early life exposure	1.006 (1.000, 1.012)	1.010 (1.003, 1.017)
Exposure trend over time	1.017 (0.900, 1.149)	1.001 (0.882, 1.136)
Averaged exposure	1.006 (1.000, 1.013)	1.010 (1.003, 1.017)

*adjusted for sex, maternal education, household monthly income, population density and neighbourhood socioeconomic deprivation

Table 5 presents the crude and adjusted associations between the mean percentage of non-tree vegetation area and behavioral problems at 7 years of age. In the crude models, higher percentages of non-tree vegetation showed a protective effect across all buffers, as well as at birth for 250-meter and 500-meter buffers. Similarly, in the adjusted models, a protective effect was observed for all buffers, both at birth and for mean exposure.

Table 5 - Associations (OR, 95%CI) between mean percentage of non-tree vegetation area and behavioural problems at 7 years of age (Generation XXI, n=6269)

	[OR (95%CI)] reported	
	Crude model	Adjusted model*
Mean percentage of non-tree vegetation		
area within 100 m		
Early life exposure	0.991 (0.983, 1.000)	0.986 (0.976, 0.996)
Exposure trend over time	0.923 (0.789, 1.079)	0.929 (0.791, 1.090)
Averaged exposure	0.992 (0.984, 1.000)	0.987 (0.979, 0.996)
Mean percentage of non-tree vegetation		
area within 250 m		
Early life exposure	0.990 (0.981, 0.999)	0.985 (0.976, 0.995)
Exposure trend over time	0.933 (0.806, 1.079)	0.930 (0.801, 1.080)
Averaged exposure	0.990 (0.982, 0.998)	0.986 (0.978, 0.995)
Mean percentage of non-tree vegetation		
area within 500 m		
Early life exposure	0.990 (0.980, 0.999)	0.986 (0.976, 0.996)
Exposure trend over time	0.930 (0.799, 1.084)	0.924 (0.790, 1.081)
Averaged exposure	0.989 (0.980, 0.998)	0.986 (0.976, 0.995)

*adjusted for sex, maternal education, household monthly income, population density and neighbourhood socioeconomic deprivation

Table 6 presents the crude and adjusted associations between mean percentage of tree coverage area and behavioural problems at 7 years of age. No statistically significant effects were observed.

Table 6 - Associations (OR, 95%CI) between mean percentage of tree coverage area and behavioural problems at 7 years of age (Generation XXI, n=6269)

	[OR (95%CI)] reported	
	Crude model	Adjusted model*
Mean percentage of tree coverage area within 100 m		
Early life exposure	0.998 (0.983, 1.012)	0.989 (0.973, 1.004)
Exposure trend over time	1.060 (0.851, 1.322)	1.137 (0.911, 1.419)
Averaged exposure	0.999 (0.985, 1.012)	0.992 (0.977, 1.006)
Mean percentage of tree coverage area within 250 m		
Early life exposure	0.994 (0.979, 1.008)	0.985 (0.970, 1.000)
Exposure trend over time	1.024 (0.835, 1.254)	1.089 (0.887, 1.336)
Averaged exposure	0.994 (0.981, 1.008)	0.988 (0.973, 1.001)
Mean percentage of tree coverage area within 500 m		
Early life exposure	0.995 (0.982, 1.008)	0.988 (0.974, 1.002)
Exposure trend over time	1.016 (0.950, 1.086)	1.029 (0.962, 1.102)
Averaged exposure	0.996 (0.984, 1.009)	0.990 (0.977, 1.003)

In Table 7, we can find the path analysis for all the statistically significant associations found between the different greenness measures and the existence of behavioural problems. As can be observed, the only mediator that explained (in most exposure measures) part of the effect of greenness was the HADS score of the mother, in which more greenness was associated with a higher score and consequently higher odds of reporting behavioural problems.

273 Table 7 – Paths analysis (OR, 95%CI) for the different exposure variables that had statistical
 274 significance in the adjusted models and behavioural problems at 7 years of age (Generation
 275 XXI, n=6269)

	Sleep	NO ₂	PM _{2.5}	Physical Activity	HADS of the Mother
NDVI within 100 m					
Averaged exposure	0.9996 (0.9954, 1.0026)	0.9804 (0.9031, 1.0594)	1.0046 (0.9610, 1.0462)	0.9998 (0.9953, 1.0029)	1.0294 (1.0081, 1.0531)
NDVI within 250 m					
Early life exposure	0.9995 (0.9952, 1.0025)	0.9789 (0.8982, 1.0759)	1.0041 (0.9617, 1.0476)	0.9998 (0.9965, 1.0024)	1.0335 (1.0136, 1.0539)
Averaged exposure	0.9995 (0.9946, 1.0032)	0.9901 (0.8890, 1.1091)	1.0086 (0.9608, 1.0634)	0.9998 (0.9960, 1.0031)	1.0361 (1.0133, 1.0620)
NDVI within 500 m					
Early life exposure	0.9995 (0.9953, 1.0024)	0.9872 (0.8862, 1.0949)	1.0046 (0.9689, 1.0439)	0.9998 (0.9952, 1.0023)	1.0396 (1.0187, 1.0635)
Averaged exposure	0.9996 (0.9953, 1.0023)	1.0063 (0.8846, 1.1362)	1.0090 (0.9579, 1.0610)	0.9998 (0.9951, 1.0024)	1.0434 (1.0196, 1.0736)
Mean percentage of non-vegetated area within 100 m					
Early life exposure	1.0000 (1.0000, 1.0000)	1.0000 (0.9996, 1.0005)	1.0000 (0.9997, 1.0002)	1.0000 (1.0000, 1.0000)	0.9998 (0.9997, 0.9999)
Averaged exposure	1.0000 (1.0000, 1.0000)	1.0000 (0.9995, 1.0005)	1.0000 (0.9997, 1.0002)	1.0000 (1.0000, 1.0000)	0.9998 (0.9997, 0.9999)
Mean percentage of					

non-vegetated					
area within 250					
m					
Early life	1.0000	1.0000	1.0000	1.0000	0.9998
exposure	(1.0000, 1.0000)	(0.9995, 1.0005)	(0.9997, 1.0002)	(1.0000, 1.0000)	(0.9997, 0.9999)
Averaged	1.0000	0.9999	0.9999	1.0000	0.9998
exposure	(1.0000, 1.0000)	(0.9994, 1.0004)	(0.9997, 1.0002)	(1.0000, 1.0000)	(0.9997, 0.9999)
Mean					
percentage of					
non-vegetated					
area within 500					
m					
Early life	1.0000	1.0000	1.0000	1.0000	0.9998
exposure	(1.0000, 1.0000)	(0.9994, 1.0006)	(0.9998, 1.0002)	(1.0000, 1.0000)	(0.9997, 0.9999)
Averaged	1.0000	0.9999	1.0000	1.0000	0.9998
exposure	(1.0000, 1.0000)	(0.9993, 1.0006)	(0.9997, 1.0002)	(1.0000, 1.0000)	(0.9996, 0.9999)
Mean					
percentage of					
non-tree					
vegetation area					
within 100 m					
Early life	1.0000	1.0000 (0.9994,	1.0000 (0.9998,	1.0000 (1.0000,	1.0002 (1.0000,
exposure	(1.0000, 1.0000)	1.0005)	1.0003)	1.0000)	1.0004)
Averaged	1.0000	1.0000	1.0001	1.0000	1.0002
exposure	(1.0000, 1.0000)	(0.9995, 1.0006)	(0.9998, 1.0003)	(1.0000, 1.0000)	(1.0000, 1.0003)
Mean					
percentage of					
non-tree					
vegetation area					
within 250 m					
Early life	1.0000	1.0000	1.0001	1.0000	1.0001
exposure	(1.0000, 1.0000)	(0.9994, 1.0006)	(0.9998, 1.0003)	(1.0000, 1.0000)	(1.0000, 1.0003)

Averaged	1.0000	1.0001	1.0001	1.0000	1.0001
exposure	(1.0000, 1.0000)	(0.9995, 1.0007)	(0.9998, 1.0004)	(1.0000, 1.0000)	(1.0000, 1.0003)
Mean					
percentage of					
non-tree					
vegetation area					
within 500 m					
Early life	1.0000	1.0000	1.0000	1.0000	1.0002
exposure	(1.0000, 1.0000)	(0.9993, 1.0006)	(0.9998, 1.0003)	(1.0000, 1.0000)	(1.0000, 1.0004)
Averaged	1.0000	1.0001	1.0001	1.0000	1.0002
exposure	(1.0000, 1.0000)	(0.9994, 1.0008)	(0.9998, 1.0003)	(1.0000, 1.0000)	(1.0000, 1.0003)

276

277 4. Discussion

278 Being born and living in a residential neighborhood with higher greenness was associated with a
279 lower report of behavioral problems. This was true for different distances around the residence
280 (100, 250 and 500 meters) for greenness measured with NDVI (except at birth for a radius of 100
281 meters) and also for mean percentage of non-tree vegetation area. Inversely, higher mean
282 percentage of non-vegetated area was associated with more behavioral problems being reported.
283 Interestingly, mean percentage of tree coverage area was the only greenness measure that was
284 unrelated to the report of behavioral problems regardless of buffer or moment of measurement of
285 the exposure, highlighting the complexity of green space effects on child psychology. Among the
286 five mediators considered, the only one that partially explained the observed effect was the
287 mother's HADS score. Higher levels of greenness were associated with an increased HADS score,
288 which, in turn, was linked to a greater reporting of behavioral problems.

289 Higher early life exposure to greenness measured as NDVI (at 250 meters and 500 meters) and
290 mean percentage of non-tree vegetation area (for all distances) was associated with lower report
291 of behavioural problems. Inversely, higher early life exposure to non-vegetated areas was
292 associated with a higher report of behavioural problems. Exposures at birth might have a relevant
293 effect since the plasticity of the brain is higher [41]. For example, there was a positive association

294 between NDVI at birth and the Mental Development Index and Psychomotor Development Index
295 at two years of age [42].

296 The average exposure during the seven years was also positively associated with fewer reported
297 behavioral problems. In another study, the mean exposure to urban green spaces at a buffer of
298 800 meters was positively associated with higher performance and total IQ at 10 years of age [29].
299 This is in line with the findings of this study since lower cognitive development is associated with
300 higher behavioural problems [43].

301 Exposure trend over time to greenness was not associated with the report of behavioural problems.
302 This lack of association with exposure variability might be due to several factors. Without
303 information regarding behavioural problems at each moment the exposure was measured, it is
304 difficult to understand the significance of exposure changes. It's possible that the effects of
305 greenness on behavior are more immediate, with the benefits arising from the current opportunity
306 for use, meaning that only changes in greenness at short intervals are relevant. It can also be due
307 to the fact that beneficial effects occur more at young ages [44], making the exposure trend over
308 time less relevant. More than variations throughout time, the averaged exposure during the seven
309 years seems to be the relevant factor.

310 The study explored various metrics to capture different facets of greenness in residential areas.
311 The NDVI, a measure reflecting the presence of chlorophyll and, thus, green vegetation, was one
312 of these metrics. When breaking down greenness into more specific categories, such as the
313 percentage of area covered by trees versus non-tree vegetation (like grass), it was the non-tree
314 vegetation that appeared to have a more significant positive impact on reducing behavioral
315 problems reported by parents. This is not entirely unexpected since different green characteristics
316 can have different effects by different pathways. For example, in a study focused on designing
317 urban parks, grass was rated higher than trees in their capacity for restoration [45]. In fact, in a
318 study that assessed the effect of different types of green characteristics on well-being, it was found
319 that grass contributes more to the positive effect of well-being than trees. Several possible
320 explanations are proposed, namely that grass can suggest more pleasant activities, that the closer

321 interaction with grass (when compared to trees) leads to stronger restoration, and also that the
322 possibility to explore more freely the space also leads to greater restoration [46].

323 Most of the results found were partially mediated by the effect of greenness in the mother's mental
324 health (up to 4.34%), with children exhibiting behavioural problems as a response to parents'
325 depression [21]. However, the effect of greenness in the mother's mental health was in the
326 opposite direction of what would be expected, with higher greenness being associated with higher
327 HADS scores [47]. It is possible that specific characteristics of greenness can be affecting
328 differently children and their mothers. The same space can be found to lead to restoration in
329 children and the same space promote a feeling of danger to their mothers. The other mediators
330 did not show statistical significance. However, contrasting with our findings, in another study, it
331 was shown that mediation by a reduction of PM_{2.5} could be a pathway to better childhood
332 neurodevelopment [42].

333 This study brings various merits to the literature. It is one of the few studies so far that uses a life-
334 course approach to assess the association between green spaces and behavioural problems, which
335 is an approach that can help understand if there are critical periods [24]. It is also the first (to the
336 best knowledge of the authors) that assesses not only the mean exposure through life but also the
337 exposure at birth (which was found to be associated with behavioural problems) and the trend of
338 exposure throughout time. It was also the first that assessed the association between greenness
339 and behavioural problems using various greenness measures. In the future, it would be important
340 to complement these measures with measures of frequency and type of use of green spaces. It also
341 used a comprehensive set of plausible mediators to clarify the pathways by which green spaces
342 can bring their effect.

343 This study has also various limitations that should be identified. Only measures of accessibility
344 were used, which limits information regarding specific features of the space that can influence
345 their use, namely the safety, availability of equipment, type of flora (although the use of different
346 accessibility measures tries to minimize this limitation) [48]. Also, although the resolution of
347 NDVI was high, the same was not true for mean percentage of non-vegetated area, mean

percentage of non-tree vegetation area and mean percentage of tree coverage area, so increases in resolution could bring more accurate results and reduce exposure misclassification. Nevertheless, despite the differences in spatial resolutions, the results obtained using greenness measures derived from MODIS and Landsat were rather consistent, which can be interpreted as a sign of robustness in our findings. The small variations in all greenness measures over time may reduce the power of analysis and, consequently the likelihood to find a significant association between the exposures (especially variations in exposure over time) and children's behavioural problems. The assessment of different mediators also has some limitations. It was not possible to identify which physical activity was performed specifically in greenspaces. Finally, because the outcome is reported by the parents, it is impossible to assess if this was due to mothers with higher HADS reporting more frequently behavioural problems in children, or if in fact children have more behavioural problems [49]. Additionally, behavioral problems were assessed through a single subjective item, not through a validated psychometric scale. The question was based on caregiver (or teacher) suspicion and not on a clinical diagnosis, which may have led to misclassification or reporting bias. Caregivers may differ in their thresholds for recognizing or reporting behavioral difficulties, and social or cultural factors could influence their responses. While this question captures meaningful concerns raised by adults responsible for the child's care, it lacks diagnostic precision.

5. Conclusion

It was observed that greenness, particularly in the form of non-tree vegetation, was associated with a lower prevalence of reported behavioral problems in children. Hence, increasing the provision of greenspaces around residential neighbourhoods can be an effective public measure to reduce behavioural problems in children.

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378

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394

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Table 1 - Characteristics of participants (Generation XXI, n=6269)

Characteristic	n (%) or mean (SD)
<i>At birth</i>	
Sex [female, n (%)]	3216 (51.30%)
Maternal education	
Primary (≤ 9 years)	2683 (42.79%)
Secondary (10–12 years)	1849 (29.49%)
Tertiary (> 12 years)	1737 (27.71%)
Household monthly income (€)	
≤ 1000	1970 (31.42%)
1001-1500	1681 (26.82%)
> 1500	2618 (41.76%)
Neighbourhood socioeconomic deprivation	0.09 (2.69)
Population Density (inhabitants per km ²)	9078 (8678)
<i>At 7 years</i>	
Reported behavioural problems (yes/no)	793 (12.65%)
Physical Activity (hours/week)	3.01 (2.47)
NO ₂	27.36 (6.03)
PM _{2.5}	13.69 (1.04)
HADS of the mother	12.13 (6.53)
Sleep duration (hours)	10.21 (0.60)

HADS: Hospital Anxiety and Depression Scale

Table 2 - Exposure to greenness in the residential neighbourhood (Generation XXI, n=6269)

Exposure variables	Mean (SD)		
	At birth	At 4 years	At 7 years
NDVI			
100 m	0.163 (0.077)	0.181 (0.073)	0.206 (0.060)
250 m	0.201 (0.075)	0.214 (0.072)	0.230 (0.059)
500 m	0.222 (0.072)	0.234 (0.069)	0.243 (0.058)
Mean percentage of non-vegetated area			
100 m	33.82 (14.84)	33.95 (14.71)	31.35 (14.17)
250 m	33.12 (14.41)	33.28 (14.26)	30.82 (13.60)
500 m	31.65 (13.45)	31.79 (13.15)	29.62 (12.39)
Mean percentage of non-tree vegetation area			
100 m	57.55 (11.04)	57.86 (11.28)	58.76 (11.11)
250 m	57.95 (10.48)	58.22 (10.65)	59.02 (10.45)
500 m	58.63 (9.28)	58.82 (9.21)	59.29 (8.99)
Mean percentage of tree coverage area			
100 m	8.63 (6.76)	8.20 (6.39)	9.89 (6.94)
250 m	8.92 (6.78)	8.50 (6.56)	10.16 (7.00)
500 m	9.72 (6.93)	9.39 (6.94)	11.09 (7.28)

Table 3 - Associations (OR, 95%CI) between NDVI and behavioural problems at 7 years of age
(Generation XXI, n=6269)

	[OR (95%CI)] reported	
	Crude model	Adjusted model*
NDVI within 100 m		
Early life exposure	0.638 (0.203, 1.97)	0.285 (0.079, 1.02)
Exposure trend over time	0.005 (0, 6.67x10 ⁶)	115.171 (0, 8.83 x10 ¹¹)
Averaged exposure	0.540 (0.164, 1.749)	0.242 (0.064, 0.907)
NDVI within 250 m		
Early life exposure	0.459 (0.150, 1.392)	0.22 (0.063, 0.753)
Exposure trend over time	0.006 (0, 5.03x10 ⁶)	12.045 (0, 3.65x10 ¹⁰)
Averaged exposure	0.36 (0.109, 1.17)	0.165 (0.044, 0.608)
NDVI within 500 m		
Early life exposure	0.441 (0.142, 1.356)	0.246 (0.071, 0.843)
Exposure trend over time	0.018 (0, 2.81x10 ⁷)	1.42 (0, 6.80x10 ⁹)
Averaged exposure	0.347 (0.103, 1.159)	0.18 (0.048, 0.676)

*adjusted for sex, maternal education, household monthly income, population density and
neighbourhood socioeconomic deprivation

Table 4 - Associations (OR, 95%CI) between mean percentage of non-vegetated area and behavioral problems at 7 years of age (Generation XXI, n=6269)

	[OR (95%CI)] reported	
	Crude model	Adjusted model*
Mean percentage of non-vegetated area		
within 100 m		
Early life exposure	1.005 (0.999, 1.011)	1.009 (1.003, 1.016)
Exposure trend over time	1.022 (0.909, 1.148)	0.990 (0.878, 1.116)
Averaged exposure	1.005 (0.999, 1.010)	1.009 (1.003, 1.015)
Mean percentage of non-vegetated area		
within 250 m		
Early life exposure	1.006 (1.000, 1.012)	1.010 (1.004, 1.017)
Exposure trend over time	1.025 (0.913, 1.15)	1.002 (0.889, 1.128)
Averaged exposure	1.006 (1.001, 1.012)	1.010 (1.004, 1.017)
Mean percentage of non-vegetated area		
within 500 m		
Early life exposure	1.006 (1.000, 1.012)	1.010 (1.003, 1.017)
Exposure trend over time	1.017 (0.900, 1.149)	1.001 (0.882, 1.136)
Averaged exposure	1.006 (1.000, 1.013)	1.010 (1.003, 1.017)

*adjusted for sex, maternal education, household monthly income, population density and neighbourhood socioeconomic deprivation

Table 5 - Associations (OR, 95%CI) between mean percentage of non-tree vegetation area and behavioural problems at 7 years of age (Generation XXI, n=6269)

	[OR (95%CI)] reported	
	Crude model	Adjusted model*
Mean percentage of non-tree vegetation area		
within 100 m		
Early life exposure	0.991 (0.983, 1.000)	0.986 (0.976, 0.996)
Exposure trend over time	0.923 (0.789, 1.079)	0.929 (0.791, 1.090)
Averaged exposure	0.992 (0.984, 1.000)	0.987 (0.979, 0.996)
Mean percentage of non-tree vegetation area		
within 250 m		
Early life exposure	0.990 (0.981, 0.999)	0.985 (0.976, 0.995)
Exposure trend over time	0.933 (0.806, 1.079)	0.930 (0.801, 1.080)
Averaged exposure	0.990 (0.982, 0.998)	0.986 (0.978, 0.995)
Mean percentage of non-tree vegetation area		
within 500 m		
Early life exposure	0.990 (0.980, 0.999)	0.986 (0.976, 0.996)
Exposure trend over time	0.930 (0.799, 1.084)	0.924 (0.790, 1.081)
Averaged exposure	0.989 (0.980, 0.998)	0.986 (0.976, 0.995)
*adjusted for sex, maternal education, household monthly income, population density and neighbourhood socioeconomic deprivation		

Table 6 - Associations (OR, 95%CI) between mean percentage of tree coverage area and behavioural problems at 7 years of age (Generation XXI, n=6269)

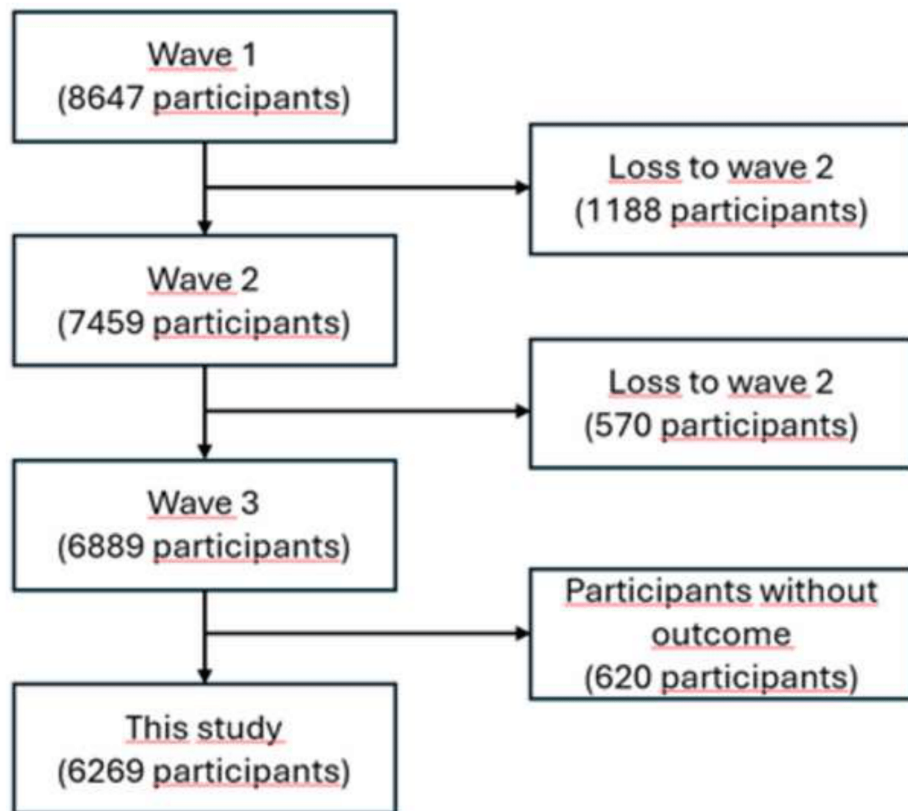
	[OR (95%CI)] reported	
	Crude model	Adjusted model*
Mean percentage of tree coverage area within		
100 m		
Early life exposure	0.998 (0.983, 1.012)	0.989 (0.973, 1.004)
Exposure trend over time	1.060 (0.851, 1.322)	1.137 (0.911, 1.419)
Averaged exposure	0.999 (0.985, 1.012)	0.992 (0.977, 1.006)
Mean percentage of tree coverage area within		
250 m		
Early life exposure	0.994 (0.979, 1.008)	0.985 (0.970, 1.000)
Exposure trend over time	1.024 (0.835, 1.254)	1.089 (0.887, 1.336)
Averaged exposure	0.994 (0.981, 1.008)	0.988 (0.973, 1.001)
Mean percentage of tree coverage area within		
500 m		
Early life exposure	0.995 (0.982, 1.008)	0.988 (0.974, 1.002)
Exposure trend over time	1.016 (0.950, 1.086)	1.029 (0.962, 1.102)
Averaged exposure	0.996 (0.984, 1.009)	0.990 (0.977, 1.003)

Table 7 – Paths analysis (OR, 95%CI) for the different exposure variables that had statistical significance in the adjusted models and behavioural problems at 7 years of age (Generation XXI, n=6269)

	Sleep	NO ₂	PM _{2.5}	Physical Activity	HADS of the Mother
NDVI within 100 m					
Averaged exposure	0.9996 (0.9954, 1.0026)	0.9804 (0.9031, 1.0594)	1.0046 (0.9610, 1.0462)	0.9998 (0.9953, 1.0029)	1.0294 (1.0081, 1.0531)
NDVI within 250 m					
Early life exposure	0.9995 (0.9952, 1.0025)	0.9789 (0.8982, 1.0759)	1.0041 (0.9617, 1.0476)	0.9998 (0.9965, 1.0024)	1.0335 (1.0136, 1.0539)
Averaged exposure	0.9995 (0.9946, 1.0032)	0.9901 (0.8890, 1.1091)	1.0086 (0.9608, 1.0634)	0.9998 (0.9960, 1.0031)	1.0361 (1.0133, 1.0620)
NDVI within 500 m					
Early life exposure	0.9995 (0.9953, 1.0024)	0.9872 (0.8862, 1.0949)	1.0046 (0.9689, 1.0439)	0.9998 (0.9952, 1.0023)	1.0396 (1.0187, 1.0635)
Averaged exposure	0.9996 (0.9953, 1.0023)	1.0063 (0.8846, 1.1362)	1.0090 (0.9579, 1.0610)	0.9998 (0.9951, 1.0024)	1.0434 (1.0196, 1.0736)
Mean percentage of non-vegetated area within 100 m					
Early life exposure	1.0000 (1.0000, 1.0000)	1.0000 (0.9996, 1.0005)	1.0000 (0.9997, 1.0002)	1.0000 (1.0000, 1.0000)	0.9998 (0.9997, 0.9999)
Averaged exposure	1.0000 (1.0000, 1.0000)	1.0000 (0.9995, 1.0005)	1.0000 (0.9997, 1.0002)	1.0000 (1.0000, 1.0000)	0.9998 (0.9997, 0.9999)
Mean percentage of non-vegetated					

area within 250					
m					
Early life	1.0000	1.0000	1.0000	1.0000	0.9998
exposure	(1.0000, 1.0000)	(0.9995, 1.0005)	(0.9997, 1.0002)	(1.0000, 1.0000)	(0.9997, 0.9999)
Averaged	1.0000	0.9999	0.9999	1.0000	0.9998
exposure	(1.0000, 1.0000)	(0.9994, 1.0004)	(0.9997, 1.0002)	(1.0000, 1.0000)	(0.9997, 0.9999)
Mean percentage					
of non-vegetated					
area within 500					
m					
Early life	1.0000	1.0000	1.0000	1.0000	0.9998
exposure	(1.0000, 1.0000)	(0.9994, 1.0006)	(0.9998, 1.0002)	(1.0000, 1.0000)	(0.9997, 0.9999)
Averaged	1.0000	0.9999	1.0000	1.0000	0.9998
exposure	(1.0000, 1.0000)	(0.9993, 1.0006)	(0.9997, 1.0002)	(1.0000, 1.0000)	(0.9996, 0.9999)
Mean percentage					
of non-tree					
vegetation area					
within 100 m					
Early life	1.0000	1.0000 (0.9994,	1.0000 (0.9998,	1.0000 (1.0000,	1.0002 (1.0000,
exposure	(1.0000, 1.0000)	1.0005)	1.0003)	1.0000)	1.0004)
Averaged	1.0000	1.0000	1.0001	1.0000	1.0002
exposure	(1.0000, 1.0000)	(0.9995, 1.0006)	(0.9998, 1.0003)	(1.0000, 1.0000)	(1.0000, 1.0003)
Mean percentage					
of non-tree					
vegetation area					
within 250 m					
Early life	1.0000	1.0000	1.0001	1.0000	1.0001
exposure	(1.0000, 1.0000)	(0.9994, 1.0006)	(0.9998, 1.0003)	(1.0000, 1.0000)	(1.0000, 1.0003)
Averaged	1.0000	1.0001	1.0001	1.0000	1.0001
exposure	(1.0000, 1.0000)	(0.9995, 1.0007)	(0.9998, 1.0004)	(1.0000, 1.0000)	(1.0000, 1.0003)
Mean percentage					
of non-tree					

vegetation area					
within 500 m					
Early life	1.0000	1.0000	1.0000	1.0000	1.0002
exposure	(1.0000, 1.0000)	(0.9993, 1.0006)	(0.9998, 1.0003)	(1.0000, 1.0000)	(1.0000, 1.0004)
Averaged	1.0000	1.0001	1.0001	1.0000	1.0002
exposure	(1.0000, 1.0000)	(0.9994, 1.0008)	(0.9998, 1.0003)	(1.0000, 1.0000)	(1.0000, 1.0003)



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Declaration of Interest Statement

Declaration of interests

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

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

4.4. Imagine your perfect park: a qualitative study on adolescents' usage of green spaces, perceived benefits and preferences.

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Imagine your perfect park: a qualitative study on adolescents' usage of green spaces, perceived benefits and preferences

Mariana Sampaio Costa ^{a*}, Diogo Queiroz Almeida ^{a,b,c*}, José Pedro Silva ^{a,b,d}, Henrique Barros ^{a,b,c}, Ana Isabel Ribeiro ^{a,b,c***} and Teresa Leão ^{a,b,c***}

^aEPIUnit - Instituto de Saúde Pública, Universidade do Porto, Porto, Portugal; ^bLaboratório para a Investigação Integrativa e Translacional em Saúde Populacional (ITR), Universidade do Porto, Porto, Portugal; ^cDepartamento de Ciências da Saúde Pública e Forenses e Educação Médica, Faculdade de Medicina, Universidade do Porto, Porto, Portugal; ^dInstituto de Sociologia da Universidade do Porto, Faculdade de Letras da Universidade do Porto, Porto, Portugal

ABSTRACT

Green spaces are essential urban infrastructures. They represent cost-effective interventions to reduce health inequities and contribute to climate-resilient cities and adolescents' health and well-being. Nevertheless, evidence suggests they are underused by adolescents, especially in Southern Europe. We explored the perspectives of adolescents on their use of green spaces (including frequency of use, activities performed, and types of space), perceived benefits, and preferences regarding green spaces' characteristics. We performed seven online focus groups with 34 adolescents (15–16 years old) recruited from the Generation XXI cohort (a population-based birth cohort from the Porto Metropolitan Area, Portugal), stratified by socioeconomic status. Data were analyzed thematically by a deductive-inductive approach. Participants reported regular use of green spaces to perform physical activity, rest, and socialize. They perceived associated benefits for their general well-being and respiratory and mental health. The views shared by the participants suggest that the perfect park was idealized as large and multifunctional, providing a diversity of equipment and sufficient vegetation. It should be close to school and residential neighborhoods, upkeep, and made dynamic by the organization of cultural or sports events. Youth-led perspectives in urban planning might improve adolescents' use of green spaces and encourage sustainable and equitable health-promoting urban environments.

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Adolescent health; green spaces; health policy; qualitative research; urban health; urban planning

Introduction

Green spaces benefit individuals' health throughout life (Hartig *et al.* 2014). During childhood and adolescence, in particular, exposure to green spaces has been associated with less obesity (Jia *et al.* 2021), better respiratory function (Queiroz Almeida *et al.* 2022), higher cognition (Almeida *et al.* 2022), and less risky behaviors (Mennis *et al.* 2021). The beneficial effects of green space on mental health are the best documented (Gascon *et al.* 2015), and recent evidence makes them measurable in practice, showing that urban green space interventions, namely green corridors, can significantly improve mental health burden across the urban population, reducing annual antidepressant use and visits to mental health specialists by 13% (Vidal Yañez *et al.* 2023). Other than health benefits, urban green spaces promote social (Mitchell and Popham 2008, Mitchell *et al.* 2015, Kabisch *et al.* 2017, van den Bosch and Nieuwenhuijsen 2017) and environmental sustainability, being an important

urban strategy for adapting to and mitigating climate change (Kabisch *et al.* 2017).

Considering the physical, mental, and social health benefits provided by green spaces, these should be considered as important elements in public health interventions aimed at tackling all major threats identified for adolescents' health and well-being.

Despite the expected positive health impacts, multi-country investigations showed that adolescents use green spaces infrequently (Rigolon 2017, Veitch *et al.* 2017), particularly in southern European cities (Van Hecke *et al.* 2016, 2018). The less frequent use of these spaces may be due to cultural factors, as well as contextual factors, such as the distance and crowding of these spaces, their inadequate maintenance, or even the absence of equipment or facilities (Dai *et al.* 2023). In the Portuguese Porto Metropolitan Area, as in most southern European cities, urban green spaces occupy only 1.5% of the total urban area, half the European average (3%) (Copernicus Programme

CONTACT Ana Isabel Ribeiro  ana.isabel.ribeiro@ispup.up.pt  Instituto de Saúde Pública, Universidade do Porto, Rua das Taipas, n° 135, Porto 4050-600, Portugal

*Equal contributors.

**Equal coordinators.

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2018). The scarcity of green spaces tends to be especially evident in the most deprived neighborhoods (Astell-Burt *et al.* 2014), where usually there is also lower accessibility to high-quality, well-maintained urban green spaces, as it is the case of Porto (Hoffmann *et al.* 2017).

Adolescents' needs and desires regarding green spaces tend to be neglected (Gallerani *et al.* 2017). In Portugal where participatory urban planning approaches are still unusual (Ferreira 2022) adults are those usually represented, and young people are rarely consulted (Gonzalez *et al.* 2022). However, it has been previously shown that adolescents are particularly willing to participate in urban planning and green spaces design (Gallerani *et al.* 2017). This might contribute to improving not only the quality and use of green spaces but also foster their social capital (Ozer and Piatt 2017).

A dynamic model of adolescent health urbanism proposed by M. Knöll and J.J. Roe emphasized youth-led participatory urban design and planning, and place affordances, integrating thus both person and place characteristics (Knöll and Roe 2017). Four types of place affordances were identified – physical, emotional, social, and digital ones. These constitute opportunities for adolescent health and well-being in the built environment, linked with mechanisms that underlie the association between exposure to green spaces and health, such as the promotion of healthy diets and physical activity; relaxation and attention restoration; and social interaction (Hartig *et al.* 2014). Yet, as these authors suggest, the specific attributes or characteristics of green spaces that foster affordances are poorly understood, and qualitative measures of how adolescents use and perceive them are needed to build comprehensive and inclusive urban environments (Knöll and Roe 2017).

This qualitative study explored the perspectives of adolescents from the Porto Metropolitan Area, Portugal, inquiring on their use of green spaces (including frequency of use, activities performed, and type of space), as well as their perceived benefits and preferences regarding green spaces' characteristics.

Methods

We conducted focus groups to allow us to collect adolescents' personal opinions and also emergent, confluent, or divergent ideas resulting from the interaction between participants (Morgan 1996). This qualitative methodology is particularly valuable when conducting research about disempowered populations, such as children and adolescents, that may be more reluctant to share their opinions in a person-to-person situation (Peterson-Sweeney 2005). The data were analyzed by deductive-inductive thematic analysis (Fereday and Muir-Cochrane 2006).

Participants and setting

Participants were recruited from the Generation XXI cohort, a population-based birth cohort that follows children living in the Porto Metropolitan Area since 2005–2006 (Larsen *et al.* 2013). The Porto Metropolitan Area is the second-largest metropolitan area of Portugal. It is located in the northern region of Portugal and has a population of 1.7 million (*População residente (N.º) por Local de residência* 2021) inhabitants.

At the cohort onset, a total of 8495 mothers were invited to have their newborns participate. As such, 8467 newborns were recruited at the five public maternities of the area, which then accounted for 95% of the region's births (Larsen *et al.* 2013).

For this study, we selected participants from Generation XXI – now adolescents aged 15 to 16 – residing in the cities of the Porto Metropolitan Area. This criterion was critical as, for the purpose of this study, we intentionally excluded the perspectives of adolescents residing in more rural areas, where agricultural and natural green spaces, rather than urban green spaces, predominate. The study area presents a shortage of green infrastructure and a large degree of socioeconomic inequality, with 4.4% of the population receiving the Social Integration Income (a social support program that encompasses monetary support and a social insertion contract to help integrate the individuals in the community), while the nationwide percentage is 2.5% (*Beneficiárias/os do rendimento social de inserção* 2021).

All eligible participants were stratified into quintiles according to SES, defined both by the household income and the socioeconomic deprivation level of the respective residential neighborhood (Ribeiro *et al.* 2018). After stratification, they were randomly selected from the lowest and highest SES quintiles. A total of four focus groups for each stratum (eight in total) with up to eight participants were deemed necessary to ensure saturation (Guest *et al.* 2016). An equal proportion of female/male participants was established since green spaces can have different use and effects depending on sex (Sillman *et al.* 2022).

Participants' legal representatives were contacted by phone, and informed about the objectives of the study, its methodology, and how the discussion would be conducted. Afterwards an invitation to participate was made, and consent was asked. Later, an informed consent form was sent by email, to be signed by the participant and their legal representative.

Focus groups

Focus groups followed a semi-structured guide developed by the research team (Supplementary Material 1).

It explored three main macro-areas: participants' modes of using urban green spaces, perceived benefits, and preferences regarding the characteristics of green spaces. A pilot focus group with a convenience sample of eight adults from outside the cohort was conducted previously to test and refine the guide.

Considering participants' availability, focus groups were scheduled between 5 March and 12 April 2022, online (Zoom platform). They were conducted by MSC; TL was present as a silent observer (Litosseliti 2003) and was responsible for field notes, managing unexpected events, and informing the moderator about topics to be further explored.

Discussions were audio and video recorded, so they could be then transcribed and analyzed. Participants were anonymized, and sex and SES were used to refer to quotations (translated by the authors and found between quotation marks).

Analysis

Interview transcripts were analyzed using thematic analysis, using a deductive-inductive approach as described in (Fereday and Muir-Cochrane 2006) with NVivo Release 1.5.2. A preceding thematic tree was first developed through the review of relevant literature on the topic and discussion among the multidisciplinary authors team which included three medical doctors, a geographer, and a sociologist, all with expertise in public, urban and environmental health. The tree was then redefined during thematic analysis (Fereday and Muir-Cochrane 2006) with the addition of emergent new codes and redefinition of the remaining codes. Specific codes are mentioned in bold in the text.

Participants in these focus groups shared and discussed their views on the **modes of use** of urban green spaces, namely frequency of use, activities performed in these spaces, and types of space used, their perception of the associated **benefits**, and their **preferences**, considering barriers and promoters of the use of these spaces (Supplementary Material 3).

The first two focus groups transcriptions were analyzed by both MSC and DQA independently. Afterwards, the analyses were compared, with confrontation and discussion of the differences in the coding of the transcripts. The remaining focus groups transcriptions were analyzed either by MSC or by DQA. Doubts were discussed between the two and, when no consensus was reached regarding how to code a specific part of the transcription, a third author was consulted to reach a final decision concerning how to code that specific transcript.

Ethical considerations

Ethical approval for this study was obtained from the Ethics Committee of Instituto de Saúde Pública da

Universidade do Porto [CE21200]. The assembling of Generation XXI cohort was initially approved by the Ethics Committee of the Faculdade de Medicina da Universidade do Porto/Hospital de São João on the 27 April 2005 and by the Portuguese Data Protection Authority.

Written informed consent was obtained from participants and their legal representatives. To preserve confidentiality, data was stored in encrypted files accessible only to the research team, and the audio-visual recordings were destroyed after transcription.

Results

Seven focus groups were performed, with a total of 34 adolescents aged between 15 and 16. The duration of the focus groups ranged between 31 and 53 minutes. The characteristics of each focus group can be found in Table 1. An eighth group was deemed unnecessary since data saturation was reached after the seventh focus group.

Modes of use: how do adolescents use green spaces?

Frequency of use

Most participants visited green spaces regularly, as part of their **daily (or several times a week) or weekly (or several times a month)** routine. **Seasonal** use was identified, as the use was more frequent during summer holidays, when adolescents, regardless of the habitual use, mentioned having more free time and using different green spaces, namely some larger spaces located away from home. The largest urban green space of the Porto Metropolitan Area (Porto City Park) was the most frequently mentioned green space during summer, whilst smaller green spaces located near home or school were preferred for day-to-day use. Female participants reported daily use more frequently. Participants from lower SES reported a higher frequency of green spaces use all year around and a less seasonal pattern.

Table 1. Characteristics of the participants.

Focus group	Number of participants	Socioeconomic status
1	1 Male 4 Female	High
2	2 Male 4 Female	High
3	2 Male 4 Female	High
4	4 Male 1 Female	High
5	2 Male 3 Female	Low
6	3 Male 2 Female	Low
7	1 Male 1 Female	Low

Activities

Physical activity and exercise, such as 'walking', 'running', 'biking', 'skating', and group sports like 'soccer', 'volleyball', 'basketball', 'handball', and 'American football', were activities frequently mentioned to be performed in green spaces. Male participants reported using green spaces for physical activity more frequently. Some participants reinforced the idea that performing physical activity in green spaces was more pleasant than doing so in urbanized areas: *(I think it is a good space to do physical exercise, for example, because it is greener, there is more nature, it is more pleasant to run than, for example, a more urban space).* – Female, High-SES).

While some participants reported enjoying being alone in green spaces *(alone, when I want to clear my head).* – Male, Low-SES), all participants, regardless of sex and SES, reported using green spaces for **sociability** purposes, explicitly or implied in other group activities, such as exercise or having meals. Most adolescents used these spaces to interact with **peers** *(there is a small park near my school where I can go with my friends. We go there after lunch usually).* – Male, Low-SES), with **family members** *(when I go with my family is more to stroll around or to talk).* – Female, High-SES), and occasionally to **meet new people**, as highlighted by one participant: *(to meet new people, because parks also help with that).* – Female, High-SES).

Other participants mentioned **walking the pets** *(I go every day to walk my dogs in the woods nearby my home).* – Female, High-SES), having **meals** *(Having lunch sometimes also, we either go get food or we order it and eat there).* – Male, High-SES), or doing **creative and cultural activities**, such as reading and writing *(I like to read in green spaces).* – Female, High-SES), doing photography *(I get those images of the sunset in my head, I take lots of pictures also).* – Female, High-SES), and playing music *(I take my guitar or accordion and sometimes I take someone who also plays [musical] instruments and we go there and we play during the afternoons).* – Male, Low-SES).

Types of green spaces used

Public urban parks and gardens freely accessible to the public were the types of green spaces more commonly reported to be used by participants. Some also reported visiting **semi-natural green** spaces (wild green spaces that underwent some degree of human intervention), such as urban forests and meadows. Few participants reported using **paid public parks and gardens** like zoological gardens.

Perceived benefits: how do adolescents perceive green spaces' impact on their health and well-being?

Adolescents perceived **health benefits** related to the contact with nature in these spaces over a wide range

of health domains – social, physical, and mental. Two dimensions were more often reported: **respiratory health and well-being and relaxation**.

Concerning **respiratory health**, participants perceived the air in green spaces as cleaner, which was good for their health and for the health of their family members: *(... it is always better for him (her younger brother) to breath purer air ...)* – Female, Low-SES).

Regarding **well-being and relaxation**, many participants reported that using green spaces allowed them to reach a general state of well-being *(Yes, I think it also makes me (feel healthier) ... I feel good).* – Male, High-SES), to relax *(It is much more relaxing to be outdoors ... Much calmer).* – Male, High-SES), to engage in mindfulness activities *(... for meditations, there are lots of people that likes to meditate in green spaces).* – Male, Low-SES) and to deal with their daily life stressors, such as the school workload *(It is to unwind a bit, to get away of the things from school).* – Female, High-SES) or excessive turmoil and noise exposure in the city *(The surroundings are usually calmer).* – Female, Low-SES).

Adolescents' preferences: what characteristics promote (or hinder) adolescents' use of urban green spaces?

Participants reported several barriers and promoters of the use of green spaces, grouped into (i) quantity and location, (ii) green spaces' intrinsic characteristics, (iii) management, and (iv) others, such as communication and events organization.

Quantity and location

Proximity was the factor most frequently mentioned as a promoter of use. Yet, conceptions of proximity to green spaces varied. Globally, walking distances of 5 to 15 minutes were preferred. Contrastingly, when distance was pointed out as a barrier to use, this was due to the need of making a trip by car or public transport: *(I seldom go, because I also have no green spaces close, so ... It's not that easy. I'd have to go by bus or car to a park, and that's the reason I don't go that often).* – Female, Low-SES). Nevertheless, regular users were willing to travel greater distances to reach them, either because they use some sports equipment regularly *(Me and my friends we go to a park where there is a basketball field (...) from my school to the park, I don't know ... It usually takes me half an hour or 40 minutes, no more than that. By foot, by foot).* – Male, Low-SES), or they value green space and contact with nature *(Yes, yes, I have parks close to my house, but I wouldn't mind if they were far away. In my case, I'd go anyway. Even because we have buses or bikes ... For me it wouldn't be a big deal, it wouldn't).* – Male, Low-SES). Willingness to travel greater distance could also vary according to the park characteristics: *(I think it depends a lot on the park, because for example the City*

Park, I don't live that close it takes me half an hour by foot, more or less, but I think the landscape and being located at the beachside, and because it is a reference place, compensates for the time we take to get there.' – Female, Low-SES).

As the most cited of the promoters, proximity was referred by all participants of the Low-SES group, and ease of transport or accessibility seemed to be more relevant to girls, regardless of their SES.

In terms of **quantity**, participants were globally satisfied with the number of green spaces; still, they favored the idea of increasing their number in this area. They argued that more green spaces could increase the frequency of use (*'The more there are, I think people would feel more captivated to go at least once, or enjoy them more'* – Male, High-SES), promote more equitable access (*'maybe for me the park is near, but for other people, it is not. So it would be favorable if there were more'* – Female, High-SES) and decrease the density of users in each space (*'I think there should be more, (...) so that people instead of clustering all in one park, could be more or less evenly distributed. (...) it would make it much more appealing to everybody'* – Male, High-SES). Additionally, a higher number of these spaces would be beneficial from an environmental and aesthetic point of view: (*'You can never have too many green spaces in the cities, given that there's a lot of pollution and everything, and it also serves as an aesthetical form of the city'* – Male, High-SES).

When inquired about their satisfaction with the **location** of these spaces, a major concern was raised: distribution. Though green spaces might have been well distributed in cities in the past, adolescents admit that today there is a decrease in urban green-spaces in favor of grey areas: (*'Maybe they were properly located, but then more houses have been built with the time that ... not anymore! Maybe the park doesn't fit in all places anymore'* – Female, High-SES). Their implementation in the center of an urban area was regarded as favorable because green spaces would become accessible to a greater number of people, better served by public transportation, and closer to a variety of services, but this perspective was not corroborated by all participants as these locations do not allow effective separation from the urban setting: (*'Some green spaces are badly located because they have a lot of buildings around them'* – Male, Low-SES).

Green spaces' characteristics

The **size** and the **design** of urban green spaces – concerning features such as **vegetation**, **aesthetics** and **equipment** – are aspects that potentiate adolescents' use of green spaces.

Larger green spaces were associated with **lower visitor pressure**, especially important during the first months of the COVID-19 pandemic, **tranquility**, and capacity to distance from the urban settings and its

inherent characteristics. Calm spaces that isolate users from **noise and air pollution** and, **visually, from the city environment**, were preferred. Many adolescents reported they valued contact with nature, **vegetation abundance, diversity of fauna and flora**, and diversity of natural **landscapes**. These properties were linked with the restorative potential of green spaces, feelings of well-being and relaxation. Indeed, the need to be in contact with nature was one recurring motive to go to urban green spaces (*'... but also to be in contact with, say, nature'* – Male, High-SES); (*'I usually go more to walk in the park, either to socialize with people, or to interact with the animals that might be there'* – Female, Low-SES). **Aesthetics** were also highlighted by adolescents: (*'I think that the aesthetics of the park is very important because ahh ... because that simply motivates certain people more to go there.'* – Male, Low-SES), as a motivator of green space use: (*'Usually green spaces are much more beautiful'* – Female, Low-SES); (*'It's much more beautiful to write outdoors than indoors'* – Female, High-SES); (*'where there is nature it is more pleasant to run'* – Female, High-SES).

Accordingly, **high visitor pressure** or the **lack of vegetation** constrains adolescents' willingness to visit green spaces: (*'they are more artificial than natural (...) instead of being parks that enhance nature, that have for example a lot of grass, a lot of trees and so on, they don't. They are more artificial. In a certain way it demotivates a bit'* – Male, Low-SES). The lack of vegetation as a deterrent to use was mainly pointed out by Low-SES participants.

Besides vegetation, **equipment** was mentioned. The mode of use determines which type of equipment is preferred: adolescents who usually do sports value the existence of football fields, basketball hoops, and fields, or volleyball areas, while those who used these spaces to socialize value the presence of benches. Walking paths frequently emerged during the discussion, since adolescents preferred built trails/paths. Other attributes such as picnic tables, toilets, or cafes did not arise spontaneously, and views regarding their relevance were sometimes not consensual (*'Picnic tables are important to have lunch there'* – Male, High-SES); (*'It depends. I don't necessarily need them [picnic tables] to go there and play. No, they are not generally needed'* – Male, High-SES).

Preference for equipment was more pronounced for boys than for girls, regardless of their SES, being thus particularly relevant for Low-SES boys, whilst High-SES adolescents valued more the restorative properties of green spaces.

Some ideas were further put forward – minigolf and urban equipment for pets, such as dog parks – to promote adolescents' use of urban green spaces.

Adolescents seemed to prefer green spaces that allow a **diversity of possible uses**, either by their size

or by the equipment they provide with. The multifunctionality of a green space might not only serve their own interests and needs at different points in time, but also serve the needs of people who might accompany or meet them there, such as friends or family. The idea of exploring and maximizing different uses, corresponding to different profiles of users in the same park, is suggested: *(‘Even, for example, even those places, those attractive things, for example, exercise machines, or fields to play sports. More picnic tables. Each of those things for example brings a certain kind of person, but imagine I am going with my friends to the football field, there are people who can go not to play football, but they go, for example, to meet us and socialize with us there, and they can even do other things and enjoy other ... other things available in the park. I mean, a simple thing attracted many people to the park by ... by connections. And I think this is something that should be considered’.* – Male, High-SES).

Management

Conditions of **cleaning and maintenance** are of utmost importance for adolescents when deciding to go to a green space (*‘and that it is clean also, not very dirty, because when it is dirty I have a feeling like a discomfort’* – Female, Low-SES), and it is not rare that deterioration of these spaces discourages their visit: *(‘for example, the garden I have close to me could be much better looked after. The grass is ragged and it’s not as attractive as a clean lawn’* – Female, High-SES).

The **perception of insecurity** was evoked as a barrier. Insecurity could be felt because of lightning conditions *(‘Because I heard that more and more robberies are happening here because there is no lighting. (...) a friend of mine was robbed and it is as he said, if there was lighting he wouldn’t have been robbed so easily’* – Male, Low-SES), or due to the perception of the presence of drug users *(‘There’s a lot of drugged people there, and well ... I have seen some bad things there, that’s why I don’t frequent that space’* – Female, High-SES).

To overcome security issues, besides improving the **lighting** of these spaces, **cleaning** them and the existence of **staff and security officers** were perceived as relevant: *(‘I think that also the municipalities should at the very least clean up and mow the grass, it makes it look a bit safer and also cleaner’* – Female, Low-SES); *(‘I think it is very important, for example, maybe to have more ... I don’t know, for example, police and so on close to the parks, so they have more attention. Because it’s a very public space, I think it’s necessary that kind of people to keep an eye on’* – Male, Low-SES).

Maintenance, cleanliness, aesthetics, and security were mentioned more frequently by Low-SES adolescents, as facilitators of use. Female participants raised

more concerns about security as a barrier, especially Low-SES girls.

Other potential promoters of urban green spaces use

Some adolescents further suggested that the **organization and promotion of events or activities** in urban green spaces would motivate young people to visit these spaces. They suggested sports tournaments, dance activities, open-air exhibitions, traditional games, or music concerts, reinforcing the double benefit of doing a thing they like in a pleasant environment such as a park, where they could *(‘spend a different day’* and *‘breathe some fresh air’* – Female, Low-SES). The need to ensure the existence of free-to-enter green spaces was also mentioned.

Furthermore, the communication of the location, equipment, and activities occurring in urban green spaces, through a *(‘website, that informs, according to the region or location, about the existing parks and their dimension, because [the choice] also depends a lot on what use the person wants to make of the space’* – Female, High-SES), was proposed.

Finally, **price** was identified as a deterrent to the use of urban green spaces, with adolescents advocating for more free spaces *(‘It would be good if there were more free parks’* – Female, High-SES).

Discussion

Adolescents regularly use urban green spaces, especially when those are part of their daily trajectories, or close to their school and residential areas. Yet, the use increases during summer holidays as they have more free time. Adolescents perceive health and well-being benefits of the use of urban green spaces, and physical activity, sociability, and relaxation are the main motives for their use. Multifunctionality was perceived as an important promoter of the use of green spaces, both considering their dimension, equipment provision, and abundance of natural green infrastructure. Sports facilities are highly valued by adolescents, and cleanliness and maintenance were identified as priority attributes to allow the enjoyment of green spaces and a higher sense of security. Concerns about the number and distribution of urban green spaces were raised; adolescents reported preferring spaces located within a walkable distance of 5 to 15 minutes.

Adolescents’ modes of use and preferences revealed different affordances being fostered by specific attributes found in green spaces, differently for gender and SES groups, as discussed below.

Physical activity is facilitated by the existence of physical affordances in these spaces, such as sports fields or courts, trails, walking paths, and by their larger size. Physical activity was reported more frequently by male participants, who also valued more

the availability of sports equipment in green spaces when compared to female participants. These results align with the already known gender disparity in physical activity, with European 4–18-year-old girls performing around 17% less total daily physical activity than boys (Telford *et al.* 2016). This disparity is, at least in part, explained by the complex negotiations of gender roles in physically active (Spencer *et al.* 2015). Still, sports facilities were highly valued by adolescents in general, in line with what was previously found by Zhang *et al.*, 2019 (Zhang *et al.* 2019). Participants mentioned paved trails as promoters of use, and previous studies have shown that these are strongly associated with physical activity (McCormack *et al.* 2010, Zhang *et al.* 2019, Petrunoff *et al.* 2022), while fitness stations, skating areas, or sports courts are less consistently associated with it (Zhang *et al.* 2019). Regarding the size of urban green spaces, evidence suggests that larger parks are indeed associated with increased physical activity among the youth (Robertson *et al.* 2012).

Emotional affordances also emerged. Adolescents – especially females – valued the restorative potential of urban green spaces and seemed to use them more routinely than male participants. Previous studies showed that women tend to value more outdoor recreational activities (Ode Sang *et al.* 2020). As they seem to more frequently experience anxiety and depression (Van Droogenbroeck *et al.* 2018), they may use these spaces more often to cope with such mental health issues. Indeed, evidence shows that women obtain greater mental health benefits from green spaces (Fernández Núñez *et al.* 2022). In accordance, female participants in our sample attributed greater importance to low visitor pressure, diversity of natural landscapes, including abundance and diversity of existing fauna and flora, aesthetics, protection from noise or pollution from the city, and isolation from grey areas in favor of greenness. Likewise, proximity was most frequently valued by girls but less central for adolescents who use sports equipment regularly, as girls tend to use parks for relaxation and social interaction, which are static behaviors, previously associated with the valorization of accessibility (Van Droogenbroeck *et al.* 2018).

It was noted that High-SES adolescents valued more the restorative properties of green spaces than the presence of sports equipment. We hypothesize that High-SES adolescents value more the emotional affordances of green spaces, as the possibility to escape from everyday routines with tight school and extra-curricular schedules. By contrast, Low-SES adolescents, especially boys, may not have the economic capacity to do sports in gyms or clubs, opting for practicing sports in free-to-enter green spaces, valuing their sports equipment, as well as the presence of services such as toilets. Low-SES adolescents might

indeed be more dependent on neighborhood green infrastructure for physical activity practice (Romero 2005, Rigolon *et al.* 2021). This may also justify why participants from lower SES reported more frequent use of green spaces.

Sociability was another common reason to visit green spaces. Social affordances and the possibility of social interactions, especially with peers, have been recognized as important drivers of the use of public spaces by adolescents (Gearin and Kahle 2006, Lloyd *et al.* 2008). Pro-social behavior and social health were shown to be fostered by the presence of some attributes, either material ones, such as benches, or immaterial, such as shade areas, perceived safety, or tranquility of the space (Sundevall and Jansson 2020).

Physical activity, relaxation, and sociability can be directly linked to the different perceived health benefits: respiratory health, relaxation and well-being. Robust national and international studies have shown that higher exposure to green spaces was associated with better respiratory function (Queiroz Almeida *et al.* 2022), lower risk of asthma (Winnicki *et al.* 2022), and lower stress levels (Zhang *et al.* 2020). The perceived benefit for relaxation and well-being is also aligned with two widely known complementary theories: the stress-recovery theory (Ulrich 1983) and the attention restoration theory (Kaplan 1995). Emotional affordances linked with feelings of relaxation and well-being and benefits for mental health were promoted by characteristics associated with restorative environments, whose value in improving mental well-being is well supported by literature (Sundevall and Jansson 2020, Lyons *et al.* 2022). Our results reinforce their importance for adolescents (Sundevall and Jansson 2020).

Adolescents voiced a generalized demand to increase the number and size of green spaces, and concerns about their location and distribution. This finding is aligned with the UN Agenda 2030 (Nations 2015) urge for universal access to public green spaces, especially in urban areas where total greenness is below the WHO recommendations on green space, as the Porto Metropolitan Area (ISGlobal Ranking Of Cities 2023). Proximity is a very well-established facilitator of green spaces' use (Zhang *et al.* 2019, Moreno *et al.* 2021), and in this study, it was agreed by adolescents as a walkable distance covered in 5 to 15 minutes or with the same amount of time using independent modes of transport, such as bikes or skates. The same distance is proposed in international recommendations for children/adolescents' urbanism models (Askew 2018), and it is also compatible with chrono-urbanism models, such as the '15-minute city' (Moreno *et al.* 2021). Small local green spaces placed close to where people live and spend their day are, thus, necessary (Europe, W.H.O.R.O.f 2016), as these spaces are commonly used regularly by adolescents.

Despite being a major predictor of actual green spaces' use (Schipperijn *et al.* 2010, Pinto *et al.* 2021), the distance and time a user is willing to travel to reach it can increase due to the multifunctionality, size and equipment offer, or the season of the year (Van Herzele and Wiedemann 2003, Rigolon 2016, Pinto *et al.* 2021). These results raise the importance of considering different buffers when studying green spaces according to their specific characteristics.

Thus, not only size or proximity must be considered when designing urban green spaces, but also these spaces' aesthetics, abundance of vegetation, or provision of equipment, as well as cleanliness and maintenance (Sundevall and Jansson 2020, Lyons *et al.* 2022). The latter – maintenance, cleanliness, sense of security, and aesthetics – were more frequently highlighted by Low-SES adolescents than by High-SES. This may be since in the city of Porto green spaces closer to more deprived neighborhoods are in poorer condition (Hoffmann *et al.* 2017). As more vulnerable groups are more dependent on the physical environment, health advantages from urban green space could, more importantly, benefit Low-SES adolescents, especially in terms of stress reduction and improvements in mental health (Ward Thompson *et al.* 2016, Marselle *et al.* 2020). The design of urban green spaces can be an effective intervention to reduce health inequalities if access to good-quality green spaces is guaranteed (van den Bosch and Nieuwenhuijsen 2017).

Considering these findings, general measures, such as creating new green spaces or increasing their size and greenness, and improving their maintenance, cleanliness, and aesthetic qualities, may promote its use by adolescents, especially in urban areas with low green coverage. Multifunctionality, through the availability of sports equipment, the increase of vegetation, fauna, and flora, and diversification of natural landscapes has been reported as an important feature both in our study and in previous ones (Sundevall and Jansson 2020, Pinto *et al.* 2021, Wang *et al.* 2022). The organization of creative and cultural activities could also foster the use of green spaces (Gearin and Kahle 2006). As a matter of fact, using green spaces to engage adolescents in creative activities might be an important, but still underexplored, mechanism behind the associations between green space exposure and cognition (Dadvand *et al.* 2015, Bijlens *et al.* 2020, Almeida *et al.* 2022) and pro-social behaviour (Putra *et al.* 2020). Finally, the suggestion of the creation of a website, as a 'local inventory' of urban green spaces, puts forward a potential fourth category of affordances of urban green spaces. It is undeniable that digital media, particularly social media, are part of the life of adolescents. Despite associated constraints (Rideout and Robb 2018), their benefits should be maximized, and

opportunities to promote health and well-being by these means should be created. In fact, evidence suggests that social media community-related practices transform local experiences, fostering ties between the community and public urban spaces. They might constitute important bottom-up participatory tools with the potential to overcome social constraints and promote grassroots urban re-appropriation (Gatti and Procentese 2021, Gatti *et al.* 2021).

Strengths and limitations

This study has some limitations that deserve to be discussed. The inclusion of 15 and 16-years old adolescents did not allow information for other ages, of this particularly dynamic phase of life, with changes in identity, personal projects, and preferences (Bullen 2010). Adolescents from minorities, such as immigrant communities, were not represented, nor were adolescents with mobility or cognitive restrictions, who might have different needs. It is important to note that focus groups occurred during a period of easing of restrictions following COVID-19 pandemic lockdown. In this context, information collected might have been influenced by particular patterns of usage and preferences during this period and not exactly representative of typical times. However, when expressing their perspectives, rarely did the participants refer the pandemic as a motive or in association. Furthermore, we consider that pandemic period was actually an opportunity to talk about green spaces, since the awareness about the benefits of nature increased due to lockdowns (Chen *et al.* 2022, Dushkova *et al.* 2022).

Equally important are some of the strengths of this study. It included a comprehensive sample that allowed us to identify differences in gender preferences and between SES, and to identify potential strategies to reduce health inequalities. To the best of our knowledge, this is the first qualitative study exploring adolescents' modes of use of urban green spaces and their perception of its impact on health and wellbeing, as well as their perspectives on barriers and promoters of use, across gender and SES (Lyons *et al.* 2022). These inputs may inform for a more adequate and effective design of urban green spaces, especially in areas where these are overall scarce (Knöll and Roe 2017, Lyons *et al.* 2022).

Conclusion

Adolescents, a key demographic in our cities, have expressed the need for more nearby green spaces that offer safe opportunities for physical activity, relaxation, restoration, and social interaction. Based on this study, we identified seven major areas of intervention

Table 2. Seven recommendations for action.

Improve Geographical Accessibility	Increase the number and size of public green spaces, ensuring they are within a walkable distance (5 to 15 minutes) from residential locations and/or schools. Ensure all adolescents, regardless of their socioeconomic status, have access to safe and high-quality green spaces.
Enhance Multifunctionality	Improve green spaces by considering their size, equipment availability, and natural infrastructure to support diverse activities such as sports, cultural and creative pursuits, relaxation, and social interactions.
Make Sports Facilities Available and Upkeep	Recognize the value of sports facilities in green spaces as a way to boost physical activity and lessen sedentary behavior. Ask adolescents about their preferences and increase the availability of miscellaneous sports.
Address Emotional Affordances	Acknowledge the emotional affordances of green spaces, particularly for females who value the restorative effects of green space. Design aesthetically pleasing green spaces that offer tranquility, aesthetics, biodiversity, and protection from urban noise, pollution, and turmoil.
Promote Pro-Social Spaces	Create and ensure green spaces with attributes (such as safety, cleanliness, and maintenance) that encourage social interactions among adolescents and their communities. Consider incorporating urban furniture such as benches and picnic tables.
Account for Socioeconomic and Gender Differences	Acknowledge that adolescents from different genders and socioeconomic backgrounds have different preferences and needs. High-SES adolescents and females may prioritize emotional affordances, while low-SES adolescents may value the existence of sports equipment. Include adolescents in these spaces' design.
Exploit Digital Platforms	Explore the potential of digital platforms, such as creating websites and apps as 'local inventories' of urban green spaces or leveraging social media to enhance awareness and engagement among local communities.

to enhance green space use in adolescents – improving geographical accessibility, enhancing multifunctionality, making sports facilities available and upkeep, addressing emotional affordances, accounting for socioeconomic and gender differences, promoting pro-social spaces, and exploiting digital platforms – which we detail in Table 2.

In light of the perceived benefits to adolescents' respiratory and mental health, as well as their overall well-being, this study underscores the urgent need for urban planners and decision-makers to prioritize youth perspectives in urban design. This can be achieved by establishing regular youth-led participatory forums or integrating youth advisory councils in the planning process. Such inclusive approaches will ensure that urban development is not only more aligned with the needs of younger generations but also contributes to sustainable, fair and impactful changes for future generations.

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Notes on contributors

Mariana Sampaio da Costa earned her master's degree in Medicine from the Faculty of Medicine of the University of Porto in 2023. Her dissertation project focused on adolescent and urban health. She contributed to the production of the White Book for the MothER Income Inequality (MERIT) project as a writer. Currently, Mariana is in the process of exploring and defining her career path in Public Health while working as a medical resident.

Diogo Queiroz Almeida has a master's in Industrial Engineering and Management (2013), and a master's in Medicine (2019). He finished the CFA Program in 2022. He is currently finishing his PhD in Public Health. He is the author and co-author of scientific articles and oral communications.

José Pedro Silva holds a PhD in sociology, specialty of sociology of environment and territory. He has worked on several research topics, generally using qualitative methodological approaches.

Henrique Barros graduated in Medicine in 1981. He is Full Professor of Epidemiology at the University of Porto since 1999. He is currently member of the Executive Commission of the National Ethical Committee for Clinical Investigation (CEIC), President of the Institute of Public Health, University of Porto, Executive Board Member of ASPHER and Past-President of the International Epidemiological Association (2017-20). He has developed research in national and international projects in clinical and perinatal epidemiology and cardiovascular, infectious, and cancer diseases, resulting in (co)authorship of hundreds of scientific publications in international journals.

Ana Isabel Ribeiro is an epidemiologist and health geographer. She is a Researcher at the Public Health Institute of the University of Porto and the leader and founder of Lab Health and Territory where she directs a program of research exploring the impact of the neighbourhood's social and biophysical features on individuals' health. She has authored >100 publications and led major research projects on urban and environmental health. She also participated in different European projects. Moreover, Ana holds the position of Invited Assistant Professor at the Faculty of Medicine (University of Porto), being actively engaged in training and student supervision.

Teresa Leão is a medical doctor (2010) and specialist in Public Health (2019), has a master's in Public Health

(2015) and a Ph.D. in Public Health (2019). Assistant professor in the Medical Faculty of Porto University. She was a researcher in the SILNE-R project (Horizon 2020), working on the economic evaluation of tobacco control policies, an expert in the Portuguese National Health Council, and a consultant in the WHO European Office for Investment for Health and Development, in health equity. Her research mostly focuses on social determinants in health and health inequalities, and analysis of health and social policies, combining quantitative and qualitative methods. Teresa coordinates the Health and Policies LAB from the ITR.

ORCID

Mariana Sampaio Costa  <http://orcid.org/0009-0006-1878-3260>

Diogo Queiroz Almeida  <http://orcid.org/0000-0002-0527-9085>

José Pedro Silva  <http://orcid.org/0000-0003-4845-854X>

Henrique Barros  <http://orcid.org/0000-0003-4699-6571>

Ana Isabel Ribeiro  <http://orcid.org/0000-0001-8880-6962>

Teresa Leão  <http://orcid.org/0000-0002-7364-0100>

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5. DISCUSSION

5.1. Introduction to the Discussion

This thesis set out to investigate how exposure to green and blue spaces influences multiple domains of children's health in the Porto Metropolitan Area. Four studies using the G21 provided a multidimensional perspective: one study examined respiratory health (lung function) in relation to green and blue space exposure [246]; a second assessed intelligence in association with residential and school green and blue space exposure [247]; a third explored behavioural problems in childhood linked to greenness over time with a more thorough mediation analysis [248]; and a fourth used qualitative methods to understand adolescents' own perceptions, uses, and needs regarding UGS [249]. This discussion aims to integrate the main findings across these studies, their strengths and limitations, and reflect on their implications for future research and public health policies.

5.2. Integration of Main Findings

Taken together, this thesis presents a consistent message: greater exposure to green spaces (in different types of exposures) during childhood is associated with measurable benefits in respiratory health, intelligence, and behavioural well-being. Another message is that blue spaces did not show any significant association with the outcomes studied (namely intelligence and lung function).

In the lung function study [246], children who experienced increasing greenness in close proximity (within 100 meters of their residence) from birth to age 10 showed improved respiratory function, evidenced by higher forced expiratory volume (FEV₁) and mid-expiratory flow (FEF_{25-75%}) at 10 years, parameters indicative of both lung function and small-airway function. This association was evident specifically for the exposure trend over time (an increase in surrounding vegetation over time), meaning that children whose neighbourhoods became greener throughout childhood accrued respiratory advantages. To capture this life-course perspective, the study considered greenness at multiple developmental points (birth, 4 years, 7 years, and 10 years) and modelled both time-

specific exposures and cumulative trajectories. It was this trajectory measure that showed association with lung function. By contrast, access to green spaces, distance to formal parks, or proximity to blue spaces did not yield significant associations, regardless of life-course measure. The lack of detectable effects for blue spaces suggests that vegetation-driven mechanisms such as air-pollution mitigation, microclimate cooling, or immune modulation are more relevant for respiratory development than water proximity, at least in inland urban settings. The mediation analysis did not show any evidence for either the physical activity or levels of NO₂ as possible mediators.

In parallel, the intelligence study [247] found that children living closer to UGS through life scored higher on IQ tests at 10 years. Having at least one public green space (such as a park or garden) within 800 meters of the residence was associated with a higher IQ (about 1.3 points above on performance and global IQ). This effect was location-specific: residential distance mattered, whereas distance from schools did not, suggesting that unstructured, proximity-driven daily exposure may be more impactful than schoolyard greenery alone. Moreover, blue space proximity was not linked to children's intelligence, mirroring the null finding for blue space in the lung function analysis and reinforcing the idea that vegetation, not water bodies, is the primary driver of benefit in these domains. These findings highlight the importance of accessible, everyday green infrastructure near homes, which may offer sensory, social, and restorative stimuli conducive to higher intelligence.

The study focused on behavioural outcomes [248] further reinforced the beneficial role of green environments. Children who grew up with more surrounding greenness had fewer reported behavioural problems by age 7, as reported by parents. In particular, higher exposure to NDVI and to non-tree vegetation around the residence was consistently associated with lower odds of behavioural problems like hyperactivity, inattention, or aggression. Conversely, a higher proportion of non-vegetated surfaces in the neighbourhood was associated with more frequent behavioural difficulties. These findings suggest that it is not merely the presence of green spaces, but the type and quality of greenness that might influence child behavioural development. This study adopted a life-course approach similar to the lung function study. It considered greenness at multiple time points (birth, 4 years, 7 years) and derived cumulative

measures. While the detailed temporality of effects is complex, both early-life greenness and average exposure were relevant, hinting at possible sensitive periods in behavioural development. Mediation analysis provided additional insight: maternal mental health appeared to play a role in the pathway from neighbourhood greenness to child behaviour problems. Interestingly, this happened in an unexpected direction, since higher greenness was linked to higher maternal anxiety/depression scores and then higher behavioural problems in children. The other hypothesized mediators, including children's physical activity, sleep duration, and air pollution levels (NO₂ and PM_{2.5}), did not significantly explain the greenness behaviour association. Thus, the relationship between green space and behavioural development appears to be only partially explained by known mediators, suggesting there may be other psychosocial or environmental mechanisms at play (such as stress reduction or social interaction) which were not measured.

Finally, the qualitative study [249] provided an on-the-ground perspective that both complements and illuminates the quantitative findings. Adolescents value and regularly use UGS for physical activity, socializing with friends or family, and personal relaxation. They reported that spending time in parks or gardens made them “feel good,” helping them to unwind from school stress and improving their overall well-being. Some explicitly linked green space use to better respiratory health, perceiving the air in parks as “cleaner and healthier”. These subjective perceptions resonate with the objective findings of better lung function in greener areas from the quantitative study included in the thesis [246], suggesting that even young people notice the difference that a less polluted, greener environment can make on how they feel. Adolescents also articulated a clear vision of what an ideal UGS should offer: it should be large, green, and multifunctional, with abundant vegetation and amenities to support various activities (sports fields, walking paths, places to sit and socialize). Crucially, it should be well-maintained, clean, and safe, and ideally located near their home or school to be easily accessible on a daily basis. When these conditions were met, teens were willing to use UGS frequently. When they were absent, adolescents tended to avoid these spaces despite recognizing their potential benefits. This user perspective sheds light on some of the nuances behind the quantitative results. For instance, simply having a green space nearby is not enough. The

space's quality, maintenance, and perceived safety can determine whether families actually utilize it and reap the benefits. Indeed, the G21 findings showed that greenness more than measures of accessibility to green space were beneficial on lung function, which aligns with the idea that an unused or poorly maintained park may not confer health gains. Adolescents' emphasis on maintenance and security (with low-SES girls in particular voicing concerns about lighting and the presence of illicit activities in some parks) highlights that social environment and infrastructure must coalesce with greenery to create a truly health-promoting space.

5.3. Positioning within the Eco-Social Model

Interpreting these results through an eco-social lens reveals how health outcomes in childhood emerge from the dynamic interplay of environmental exposures and social conditions over time. Krieger's eco-social theory posits that individuals "embody" their social and physical environment, meaning that advantages or disadvantages in one's surroundings become biologically instantiated in health disparities [250]. In this thesis there is evidence of embodiment of the physical environment: children living in greener neighbourhoods literally breathe better (with better lung function) and think better (with higher intelligence scores) than those surrounded by concrete. Moreover, the beneficial associations of greenness persisted even after adjusting for key socioeconomic factors like family income and maternal education, suggesting that the effects are not solely due to higher SES families self-selecting greener areas. The environment itself appears to contribute additional health value [16, 247]. This aligns with an eco-social understanding that place-based features have independent roles in shaping health, above and beyond individual social characteristics [251]. At the same time, the eco-social perspective reminds us that green space does not exist in a vacuum but that it is deeply embedded in a social context that can amplify or dampen its health effects [155]. One interesting observation is the modulation of green space benefits by socioeconomic and cultural factors. The adolescents in the focus groups from lower-SES backgrounds reported using local green spaces more frequently year-round than their higher-SES peers, possibly because they rely more on free public spaces for recreation. Yet, paradoxically, those

same low-SES adolescents were also more likely to find their neighbourhood parks poorly maintained and unsafe, and low-SES girls especially voiced feeling insecure due to issues like inadequate lighting or the presence of potentially dangerous individuals [56]. This reflects a broader pattern of structural inequality (and environmental justice): deprived neighbourhoods often have fewer green spaces, and those that exist may be of lower quality or carry social risks [206]. This finding exemplifies the eco-social concept of contingent pathways. Greenness per se is advantageous, but its translation into health gains may be contingent on social factors like safety, cultural norms of park use, and community investment [155, 252]. Another aspect of the eco-social model is its emphasis on life-course. Timing matters: for lung function, increasing exposure during the first decade of life was key, whereas greenness present at birth alone was not enough to influence lung capacity [246]. This makes biological sense since lungs develop rapidly through childhood, so ongoing exposure (or lack thereof) to clean, green environments will shape their growth trajectory, consistent with the idea of sensitive developmental windows. For behaviour the greenness at birth was associated with later behavioural outcomes. One interpretation is that the early-life environment, even before a child is actively exploring parks, might set a foundation for neurodevelopment perhaps via maternal health during pregnancy or infancy [253]. From an eco-social perspective, maternal mental health could represent a plausible pathway linking neighbourhood greenness to child behavioural development, as greener environments might be expected to reduce maternal stress and support a more nurturing early-life environment [254]. However, the findings in this thesis followed the opposite direction: higher greenness was associated with higher maternal anxiety/depression scores, which in turn were associated with more behavioural problems. This unexpected pathway should be interpreted cautiously, as it may reflect contextual characteristics of specific green environments, residual confounding, or limitations in mediator measurement. This illustrates how the social (maternal mental health) and the environmental (greenness) are intertwined in affecting the child. The qualitative narratives also underscored the cumulative importance of place: adolescents lamented that urban development over time was “squeezing out” green pockets that used to exist, with new buildings replacing parks in some areas. This recognition of historical change was voiced by a participant “maybe they were properly located, but then more houses have been built...not

anymore”, and echoes the eco-social idea that historical and ongoing urban planning decisions shape current exposure and health opportunities for different communities [255].

5.4. Comparison with Existing Literature

The findings align with the growing body of literature on nature and child health, while also contributing with new evidence. A multi-cohort meta-analysis of over 35,000 children in Europe found that higher residential greenness (measured by NDVI within 300m) during childhood was associated with significantly better lung function, particularly higher FVC and FEV₁ volumes [136]. It noted that exposure in early life was not linked to lung performance, whereas exposure accumulated through childhood was, reinforcing the notion of critical exposure windows during lung development [136]. The effect sizes in G21 (β around 0.01–0.02 L increase in FEV₁ per unit increase in greenness trend) were in the same direction as the meta-analysis result (β around 0.06 L for FEV₁ per interquartile range increase in greenness). Greener environments seem to foster better respiratory development in children, likely by providing cleaner air and more opportunities for active play. While this thesis did not show any mediation by air pollution levels, literature does suggest pollution reduction as a key pathway (trees and vegetation can filter particulates and lower traffic emissions exposure) [136]. Another potential mechanism is the “biodiversity hypothesis”, with exposure to diverse environmental microbiota in greenspaces educating the immune system and reducing inflammation, benefiting respiratory health [256]. This is an emerging area of research; going forward, integrating microbiome assessments could clarify if greener childhoods lead to healthier respiratory microbiota and less allergic airway disease.

The finding that proximity to green spaces correlates with higher childhood IQ is also in line with prior studies on nature and neurodevelopment. In a pioneering study in Barcelona, Dadvand et al. found that primary school children in schools with more surrounding greenness showed significantly greater improvements in working memory and a faster developmental trajectory of attention capacity over 12 months [16]. It

highlighted school environment, whereas the results of the study in this thesis [247] emphasize residential green space, and no effect of school-based greenness on IQ was observed. This discrepancy may arise from differences in outcome (short-term intelligence vs. global IQ at age 10) or context (perhaps school greenness in Porto was uniformly low or not effectively utilized, whereas in Barcelona variation was larger). A follow-up study reported that lifelong exposure to greenness (from birth through early teens) was associated with structural changes in the brain (higher white matter volume) and better cognitive scores [257]. The findings of this thesis complement those by demonstrating an effect on a clinically relevant intelligence score and by assessing blue space exposure, an area where the literature was scarce. No benefit of blue space exposure on children's intelligence was found. Some adult studies [258, 259] suggested living near blue spaces can improve mental health and well-being, but consensus is lacking, and for cognitive outcomes in youth, this thesis is among the first analysis. It could be that any subtle cognitive benefit of blue space is overshadowed by the stronger contributions of green space in urban areas. It is also worth noting that intelligence gains associated with greenness were modest, but, at a population level, even small shifts in intelligence distribution can have meaningful implications for academic achievement and later-life outcomes [260]. The inclusion of multiple exposure time points and types is a strength relative to many earlier cross-sectional studies that often used a single greenness measure at one time. Recent literature has shown that access to actual green spaces (parks) might be more relevant for child cognition than generalized greenness. Richardson et al. in Scotland found that neighbourhood natural space and private gardens were linked to reduced behavioural difficulties in young children, with parks appearing especially important for boys and gardens for children from lower-education households [261]. These findings support the view that specific, accessible spaces where children can actively play and interact with nature may be more influential than general vegetative cover alone.

The study on behavioural problems intersects with the expanding literature on green space and child mental health. Greater exposure to nature is associated with fewer emotional and behavioural difficulties in children. A 2022 systematic review found that greenness is linked to lower risk of ADHD symptoms and diagnoses, less aggressive

behaviour, fewer internalizing problems like anxiety/depression, and better social behaviour in children [262]. This thesis reinforces these conclusions: there were fewer behaviour problems (including hyperactivity/inattention and aggression) in greener environments. This is comparable to findings from Spain's BREATHE project, which reported that children attending schools with more surrounding green had lower scores on behavioural problem checklists [263]. The study in this thesis adds nuance by examining different types of greenness. Interestingly, non-tree vegetation had a stronger inverse association with behaviour problems than did tree coverage. One possible explanation is related to use and visibility: open grassy areas are more suitable for active play, sports, and group activities that can help channel children's energy and improve social interactions, potentially reducing behaviour issues [264]. While dense tree cover may offer important benefits, like shade, noise reduction, or mitigation of air pollution, it may be less directly conducive to active play in daily settings. However, evidence shows that in specific populations greater tree canopy coverage is associated with fewer conduct problems [265], suggesting that the advantages of tree cover for behaviour may be context-dependent. The finding suggests urban greening for child health should incorporate well-designed greenspaces (a mix of open play areas, grass, and trees) as also emphasized in this thesis in the qualitative study [249]. Another new contribution is the mediation analysis, which tried to explain how greenness might translate into behavioural benefits. There wasn't evidence that increased physical activity or reduced air pollution explained the effect (unlike a study that suggested pollution reduction mediated greenness effects on cognitive development) [266]. But there was mediation via maternal mental health. In greener areas, mothers paradoxically reported slightly higher HADS scores, which in turn were linked to more child behaviour issues. Evidence suggests that large areas of open grass, often car-oriented, less walkable, sometimes inaccessible or perceived as unsafe, do not confer the same mental-health benefits as tree canopy, which offers shade, cooling and higher amenity. Socioeconomic limitations may further accentuate these patterns [114]. This finding highlights the importance of considering context and not assuming that green space uniformly improves everyone's mental health; social environment modulates outcomes, as also suggested by others [206]. Overall, the findings align with the consensus that greening is associated with small-to-moderate improvements in child behavioural health, and they underscore

emerging questions about optimal types of green space and the interplay of parent and child well-being that future studies should explore [262].

The qualitative insights from the adolescents in the qualitative study [249] also find some resonance in the existing literature on youth and green space use. Prior studies observed that European adolescents, particularly girls, report infrequent park use and identified barriers similar to those our participants mentioned: distance, lack of appealing features, and safety concerns [264]. The participants' wish list for the "perfect park" (large, lots of vegetation, sports facilities, places to relax, events to attract people) mirrors findings from other qualitative studies. A focused ethnography in the US found adolescents valued parks as places for both active recreation and finding tranquillity, and emphasized the need for a feeling of ownership and safety in those spaces (themes of "my park" and community connection) [267]. One difference is that in the study in this thesis adolescents explicitly highlighted organized events (sports tournaments, concerts, etc.) as something that would draw them to parks, suggesting that programming is as important as physical infrastructure in sustaining adolescent engagement. This is in line with research on "activation" of parks: providing structured activities can increase youth visitation and enhance perceived benefits of the space [268]. Adolescents' concerns about cleanliness and lighting agree with other studies noting that adolescents, especially girls, are sensitive to environmental cues of disorder or danger and these can deter use [264]. The literature on park equity also supports observations that low-income neighbourhoods often suffer from maintenance issues, which can essentially negate the presence of a park [206]. In Porto, as noted in an earlier study, not only are green spaces less abundant in poorer areas, but their quality is lower [56]. The qualitative data provided lived examples of this statistic. On a positive note, the adolescents recognized the potential of green spaces to improve their health and happiness. They articulated benefits like stress relief and "clean air" which reflect awareness of nature's effects that is well documented in environmental psychology [269, 270]. The fact that the participants connected their experiences to better mental and even respiratory health shows that young people can perceive environmental health links that researchers measure, a form of "experiential knowledge" that complements empirical evidence. This reinforces arguments for participatory planning approaches: adolescents themselves best

understand the features that encourage their use of parks. Actively involving youth in urban design can therefore help create spaces that are more equitable, appealing, and supportive of their health and well-being [271].

5.5. Public Health and Policy Implications

The collective evidence from these studies carries public health and urban policy implications. It strengthens the case for urban greening as a child health intervention in terms of public health. City governments and public health authorities should recognize that the design of urban spaces is not just an aesthetic or environmental concern, but also a health determinant for the paediatric population [272]. In the Porto Metropolitan Area, where green space is scarce and unevenly distributed, increasing the quantity and improving the distribution of green spaces could have a meaningful impact on population-level child health outcomes. The lung function benefits suggest that even modest increases in neighbourhood vegetation could contribute to better respiratory health [246] and potentially reduce the burden of asthma or other pulmonary conditions in children over the long term [273]. Given that early lung function tracks into adulthood and predicts chronic respiratory disease risk, interventions today (like planting street trees, creating pocket parks, or greening schoolyards) may lead to healthier adults decades later [274]. Similarly, the intelligence advantages associated with nearby parks, while small per individual, across a whole city's children could translate into improved school performance and a more educated and competent population. In economic terms, investing in urban green infrastructure might be justified not only for its environmental benefits but also for boosting human capital in the long run [260]. Policymakers should therefore view child-friendly green space provision as part of a preventive public health strategy especially in urban settings.

Urban planning must incorporate these health insights by prioritizing the creation and maintenance of UGS in residential areas. A key recommendation derived from our studies is to ensure that every child has access to a green space within a short walk from home (800-meter residential availability measure associated with intelligence in this

thesis [247], but adolescents in desired even closer proximity, 5–15 minutes walking distance [249]). This aligns with the concept of the “15-minute city”, urban neighbourhoods designed such that essential amenities (including parks) are reachable within 15 minutes on foot [275]. Spatial equity should guide the allocation of new green spaces. Disadvantaged communities often have the least access to UGS and stand to gain the most if that gap is closed [251]. From a policy perspective, this means channelling resources to “park-poor” and high-density neighbourhoods: converting vacant lots into community gardens, reclaiming underused urban land for small parks, or implementing street tree programs in areas with few yards or parks. The notion that greening can also reduce health inequalities is supported by evidence that the SES gap in certain health outcomes (like obesity or mental health) is smaller in greener neighbourhoods [276]. Therefore, urban greening should be explicitly framed as an equity-promoting intervention. However, policymakers must also be wary of unintended consequences like green gentrification, where creating attractive parks can drive up housing costs and displace low-income residents [275].

The findings also underscore the importance of quality and safety in UGS provision. Public health impact can better materialize if people feel able and willing to use the spaces. Thus, municipal agencies should not only count the number of parks but ensure these parks are well-maintained, clean, and secure. Regular maintenance (trash removal, landscaping) and infrastructure upkeep (fixing broken lights, benches, playground equipment) are fundamental. The adolescents in the thesis made it clear that a dirty or dilapidated park is essentially a non-option for them. Cities can consider participatory maintenance programs or “friends of the park” groups that involve local youth and residents in keeping parks clean. This can simultaneously improve conditions and foster a sense of ownership and safety [277]. To address security, cities can invest in better lighting (a straightforward fix mentioned by teens to deter crime in the evenings) and in measures like park rangers or community policing during peak hours. Programming and activation of green spaces emerged as another policy lever. Organizing events (sports leagues, outdoor concerts, cultural festivals) and providing facilities (sports courts, exercise equipment, picnic areas) can attract adolescents and families, turning parks into vibrant community hubs rather than idle green decor [278].

Regarding blue spaces, the absence of significant effects on lung function and cognition can suggest that, at least in this context, investments in blue infrastructure might not yield the same returns as green spaces. Nevertheless, lack of evidence of associations is not the same as evidence of no associations. For coastal or riverine cities, blue spaces often afford unique recreation and can have mental health benefits [259]. Blue spaces may improve adult mental health or physical activity in ways that indirectly benefit children. Urban planners should ideally integrate blue and green, for example by developing riverfront parks or ensuring coastal areas have green buffers, which can provide co-benefits (scenic views plus shade and air filtration). Given climate change and the need for flood management, “blue-green infrastructure” is an emerging planning focus that could serve both environmental resilience and recreation [279].

From a public health programming perspective, there are opportunities for health promotion and education. Healthcare providers and child educators could encourage families to take advantage of green spaces for physical activity and stress reduction. Paediatricians might start “park prescriptions,” an idea experimented in some cities where doctors prescribe a certain amount of outdoor time to children with obesity or ADHD [280]. Schools can also play a role: even if school greenness didn’t show a direct IQ effect in our data, greening schoolyards has demonstrated benefits (cooler play areas, more physical activity, improved attention in class) [281]. School-based programs could incorporate outdoor learning or gardening, linking environmental education with academic curricula to harness the cognitive stimulation described in the introduction (nature igniting curiosity and creativity). Additionally, as the adolescents clearly articulated, there is a willingness to use parks if conditions are right, so involving youth in the co-design of public spaces is a pragmatic step. City planning departments should consider youth advisory councils or participatory design workshops for new park projects, thus operationalizing the “youth-led perspectives” our study advocates. This can ensure that features important to younger users are included, thereby increasing usage and delivering health benefits to that demographic.

Lastly, these findings have implications for cross-sector policy collaboration. Improving UGS requires coordination between health sectors, education, transportation, and housing. When a new residential area is zoned, are UGS mandated? When assessing

proposals for infrastructure, do we consider impact on existing trees or parks, and mitigate losses? This thesis research provides concrete evidence that such considerations are justified. Furthermore, climate change adaptation policies that add urban greens (to reduce heat islands, manage stormwater) can simultaneously be health-promoting policies. Public health advocates could thus form alliances with environmental sustainability advocates to jointly push for urban greening as both a climate resilience and health equity measure [282].

5.6. Strengths and Limitations

One major strength across the quantitative studies in this thesis is the use of the G21, a large, population-based cohort with prospective data collection. The sample sizes were robust, providing adequate statistical power to detect even modest associations. The cohort's rich data allowed us to adjust for many confounders such as maternal education, family income, and neighbourhood deprivation, thereby strengthening the internal validity of the observed associations [283]. The longitudinal design and repeated exposure assessment are notable assets. By incorporating greenness exposure at multiple ages there was a life-course assessment, including cumulative exposure and timing effects. This is a step ahead of many earlier studies which often measured green space at one time. This thesis approach improves inference about potential causality and sensitive periods [284]. The inclusion of objective health measures is another strength: lung function was measured by spirometry, intelligence by WISC-III. This lends credibility to the outcome assessment and reduces measurement error in key dependent variables.

In terms of exposure measurement, there was a comprehensive GIS-based assessment of natural spaces, including NDVI (a satellite-based greenness index) and actual accessibility metrics (distance to parks, number of parks within a buffer, distance to blue spaces). This multifaceted approach is a strength because different metrics capture different dimensions. For example, NDVI trend was linked to lung function but park count was not, illuminating the possibility that greening rather than park accessibility was influencing respiratory health [285]. A novel exposure was also introduced, such as

separating tree vs. non-tree vegetation for behavioural analysis. This is a methodological strength as it begins to parse which qualities of green space are beneficial.

The integrative nature of this thesis, spanning physical, intelligence, behavioural health, and adding a qualitative component is an overarching strength. It allowed for triangulation of evidence. The qualitative findings enriched the interpretation of the quantitative results, providing context about usage and perceptions that numbers alone cannot fully capture. For instance, understanding why accessibility to parks wasn't associated with lung function became clearer when adolescents described not using distant or poorly kept parks (although the variable was assessed at age 7). Such integration enhances the validity and relevance of conclusions drawn for real-world settings.

Despite the strengths, there are also limitations to acknowledge. A primary limitation is the observational design of the quantitative studies, which means we cannot definitively establish causation [286]. Although we adjusted for many confounders, residual confounding is still possible. Families who choose to live in greener neighbourhoods might differ in unmeasured ways. Perhaps health-conscious parents both seek out green areas and engage in parenting practices that improve child outcomes (like non-smoking homes, stimulating cognitive activities). This was mitigated by controlling for socioeconomic indicators, but still, causality should be inferred carefully. There could also be reverse causation concerns in some associations. If a child had severe behavioural problems, a family might move to a quieter, greener area in hopes of helping the child, which would produce an association even if greenness had no effect. However, the life-course approach minimizes this problem, as exposure mostly preceded outcome measurement [287].

Exposure misclassification is another limitation. Green space metrics, while objective, are imperfect proxies for a child's true exposure to nature. NDVI from satellites can tell us how green an area looks, but not whether a child actually interacts with that greenness [288]. Similarly, having a park within 800 meters does not guarantee the child visits it. The qualitative study revealed instances of underutilized local parks due to safety or preference reasons. If non-users were misclassified as exposed, this would generally

bias associations towards the null (which might explain why some metrics like park count showed no effect overall) [289]. Furthermore, NDVI buffers and park distances assume a static radius of effect. The spatial resolution of land cover data was also coarser for distinguishing tree vs. grass (while NDVI was derived from Landsat imagery at 30-meter resolution, the distinction between tree canopy and non-tree vegetation relied on MODIS Vegetation Continuous Fields data at 250-meter resolution). This could introduce misclassification between vegetation types. Encouragingly, we found consistent results with both NDVI (higher resolution) and land cover (lower resolution) measures, suggesting robust findings despite this [233].

Measurement of outcomes also had some limitations. The behavioural outcome was not ideal: a single binary item asking for suspicion of behavioural problems is not as reliable or specific as a validated behavioural scale (like the Strengths and Difficulties Questionnaire or a clinical assessment). It could have led to under-reporting and worse differential misclassification, since some parents might be more inclined to label a child as “hyperactive” than others. If greener environments influence parent perceptions (mothers in greener areas reported worse mental health), it could bias reporting. Intelligence was assessed at age 10, which is a suitable age for stable IQ testing, but there were no earlier measures, which makes it impossible to assess growth over time. Also, while IQ is informative, it is one slice of cognition; other aspects like attention, memory, or academic achievement could provide a fuller picture.

Another limitation is external validity. The findings may not extrapolate to rural areas or cities with very different climates and geographies. For instance, Porto has a temperate climate and specific types of vegetation; in a tropical city or a desert city, the relationship of greenery with health (and the types of greenery used) can differ. Similarly, cultural factors in how people use public spaces vary. European studies show substantial cross-national variation in adolescents’ physical activity and public-open-space visitation [264]; the qualitative data may be most applicable to societies with similar cultural attitudes towards youth independence and outdoor play.

There is also the limitation of blue space measurement and interpretation. Distance to blue spaces was treated similarly to green spaces, but blue spaces can have different

usage patterns (fewer people live very close to water due to geography; visits to the beach might be occasional but impactful). No measure of frequency of visits to blue spaces was used, so there is a possibility that some health effects of recreational blue space exposure were missed [290]. Additionally, blue space aggregated various water bodies, and there is the possibility that, like the quality of the green space changes effects, so does the quality of the blue space. The null results for blue should be interpreted carefully given these issues [64].

The mediation analysis, while ambitious, also had limitations typical of such analyses. Some of the mediators might not have been captured accurately (physical activity was parent-reported, which is less precise than using accelerometers; maternal mental health was a short screening scale). And mediation requires strong assumptions. Mediators were treated as independent, but, in reality, they can be interrelated. The mediation findings should be seen as exploratory.

For the qualitative study, the discussions were conducted online, which might have constrained dynamics or who could participate. However, there was apparent thematic saturation. While qualitative findings aren't meant to be statistically generalizable, their congruence with findings from other cities suggests credibility [291].

6. CONCLUSION

Among this thesis a clear message emerges: our children need nature, and they need it now. The findings are more than academic results. They are the quiet echoes of an older truth, quantified anew for a modern world that has almost forgotten it. A child who cannot run on grass, who has never climbed a tree or listened to birdsong at dusk, is a child we have failed, not just emotionally or socially, but biologically. Each statistic presented is a testament to the profound gift we give children when we open the door and let them freely roam in nature. Conversely, each uptick in problems – each restless behaviour, each shallow breath, each flicker of stress – is a warning bell that rings when we confine children to a life indoors, under flickering screens and between concrete walls.

Today's cities, for all their glittering innovation, risk raising a generation that carries a deficit of nature. Richard Louv warned of “nature-deficit disorder,” the idea that alienation from nature comes with costs to children's well-being. This research makes that warning tangible and immediate. It shows that this deficit is not a distant, philosophical worry – it is here now, reflected in measurable differences in development and health that could haunt a lifetime. If a ten-year-old in 2025 breathes easier and thinks more clearly because there's a park, what does it say of our society that another ten-year-old, boxed into an apartment block with no green escape, is left wheezing and distracted? It says that we can, and must, do better.

This is a wake-up call to urban leaders, healthcare providers, educators, and to every one of us who shapes the world that children grow up in. We are standing at a crossroads in history where the value of nature can finally be quantified not only in carbon sequestered or degrees cooled, but in minds nurtured and illnesses averted. We can no longer afford to consider parks as mere pretty extras or childhood outdoor play as a nostalgic triviality. They are as essential as clean water and good nutrition. The science is affirming: a child thrives in the embrace of trees, sunlight, and water.

Imagine for a moment the city of the near future, if we heed this call. Picture urban neighbourhoods where laughter echoes from green schoolyards and every evening families stroll through leafy parks that didn't exist a decade prior. High-rise buildings are draped with vertical gardens, and rooftops bloom with community orchards. Doctors write prescriptions not just for pills, but for “forest bathing”. And those prescriptions are

filled eagerly by parents. City councils measure their success not only in economic growth but in how many children play in the summer meadows of urban commons, how many children can identify the smell of wet soil after rain. This vision is not an utopia. It is an achievable reality within our generation's grasp. The knowledge and tools are here. What remains is the courage and will to act.

If we choose not to act, the loss is almost unfathomable. We risk bequeathing to the next generation a world where childhood is stripped of wild wonder, where the keen edge of curiosity is dulled by asphalt, and ancient bonds to the earth are severed by our indifference. In such a world, children's health will pay the price. But if we take up the mantle of change, if city planners draw green into every corner of our maps, if school principals throw open the gates to nearby fields, if parents and communities rewild the spaces around them, then we can rewrite that future. We can ensure that no child grows up under glass and concrete alone, staring out at a world they feel separate from. Instead, they can be out there, knee-deep in a creek or chasing butterflies in a vacant lot turned garden, living a childhood that is not a virtual simulation, but real and rooted.

In closing, the discussion presented in this thesis is both a scientific account and a story. A story of children and nature. It is a story in which we all have a role to play in the next chapter. The evidence whispers a simple truth: give children a chance to touch nature, and nature will give back in ways that makes them healthier, wiser, and more whole. Let this be our wake-up call to bridge the distance we've created. The path forward is clear, winding through green parks and along blue rivers. We need only to take the first hopeful steps. The well-being of our children, and indeed the well-being of our cities and planet, depends on it.

7. REFERENCES

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