Connecting science with policy for sustainable development of urban ecosystems

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To Miguel, my foundation

Declaration

I, Mikaël J. A. Maes confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm this has been indicated in the thesis.

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Abstract

Challenges remain to sustainably develop urban ecosystems, in part because sustainable development has many environmental, societal and economic dimensions which are intertwined. As part of this challenge, urban ecosystems are increasingly considered to deliver human health benefits, but the association between human health benefits and urban ecosystems, and how this knowledge can inform decision-making remains unclear. Here, I explored how to sustainably develop urban ecosystems by addressing a subset of this challenge, focusing on existing scientific knowledge gaps between human health and urban ecosystem exposure, the barriers to integrate this information into urban ecosystem accounting, and use of these outputs in public policy to inform decision-making related to urban ecosystems. First, I reviewed evidence using the United Nations Sustainable Development Goals as an analytical framework to show that development of urban ecosystems cannot be addressed without addressing other non-environmental policy objectives and that cross-disciplinary work is needed to resolve the abovementioned knowledge gaps. Then, using a health dataset of approximately 6,600 children in the London metropolitan area, United Kingdom, I showed that natural environments, particularly woodland, were associated with children's cognition and mental health, while other types of natural environments had no or weaker associations. Using these insights, I then reviewed international environmental accounting rules and found that these frameworks do not facilitate integration of cognitive and mental health benefits into urban environmental accounts. Finally, I assessed the relevance of environmental accounting to the broader public policy community and showed that environmental accounts have cross-cutting relevance for public sector decision-making. Although progress has been made to understand the role of urban ecosystems for cognition and mental health, key impediments also remain within the science, environmental accounting and public policy blocking progress to sustainably develop these. I see cross-disciplinary coordination structures as indispensable to support sustainable development of urban ecosystems globally.

Impact statement

Increasing collaboration between fields of knowledge has been discussed and attempted to address key knowledge gaps, but to date still holds many practical challenges for specific decision-making contexts such as management of urban ecosystems. This thesis makes important contributions to understand relationships between fields of knowledge to sustainably develop urban ecosystems across the world and in the United Kingdom (UK) in particular. This thesis uniquely does so by bringing together the fields of environmental epidemiology, environmental accounting and environmental policy. It showcases how epidemiological research on human health benefits received from urban ecosystems can feed into environmental accounting frameworks to inform broader public sector decision-making.

The tools and knowledge developed in this thesis provide a basis for further research into advancing nature, cognition and mental health research by developing the largest epidemiological study in the UK on adolescent's cognition and mental health benefits received from exposure to different types of urban ecosystems. This research has been presented to a wide audience from specialised ecological conferences to broad international ecosystem services conferences. The work in this thesis has also been published or accepted for publication in leading international peer reviewed journals, including the journals '*Ecosystem services*', '*Environmental Science & Policy*' and '*Nature Sustainability*'.

There is interest in this research from a range of organisations responsible for the design and management of urban built and natural environments, including architecture and urban design, and environmental consultancy, as well as public bodies including local and national authorities such as the Greater London Authority, the Department for Environment, Food & Rural Affairs (Defra), the Environment Agency and public health bodies. For example, I completed a secondment at the Environment Analysis Unit of Defra where I worked in close consultation with public servants to inform the scope of my research and my results informed Defra's engagement strategy with other UK Government

departments such as the Department for Transport and the Department of Health and Social Care. I also presented part of my research at a governmental workshop to formulate a cross-departmental strategy on the natural environment. Interested stakeholders representing some of these organisations have been consulted throughout the project and the research will be disseminated through this network. Immediate impact is likely to involve actors within the UK and beyond.

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Firstly, and most importantly, to my dear Miguel. Thank you for having confidence in me always.

To my parents, Lidia and Roger, wo have supported me in so many ways to pursue a career that I love, and to my family and friends with whom I would not have done this without.

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I am very grateful to have been surrounded by wonderful colleagues at UCL's Centre for Biodiversity and Environment Research, the people at the Department of Epidemiology and Biostatistics at Imperial College London and the Yale School of the Environment. I would also like to thank Alastair Johnson, Colin Smith and Victoria Burch from the Environment Analysis Unit at Defra. I had a splendid time working with them and the rest of the team during my research placement at Defra.

Finally, I would like to thank the management team of the London NERC DTP programme for providing the essential funding needed to do this and placing your trust in me. Through your financial support, I was given the opportunity to pursue my ambitions to do this Ph.D. project, and my desire to further build a career in sustainable development.

Attribution

The work presented in Chapter 2 was conducted in collaboration with Kate E. Jones, Mireille B. Toledano and Ben Milligan. The study was conceived by myself and B.M., I undertook the literature review and conducted all other analyses. All authors contributed to the paper. This work was published at the journal *Environmental Science & Policy* in March 2019, and the published paper is provided in Appendix A (Maes et al., 2019).

The work presented in Chapter 3 was conducted in collaboration with Monica Pirani, Elizabeth R. Booth, Chen Shen, B.M., K.E.J. and M.B.T. The study was conceived by myself, K.E.J. and M.B.T. The original health dataset of adolescents' cognition and mental health was developed and maintained by the Study of Cognition, Adolescents and Mobile Phones (SCAMP) which is managed by MBT at Imperial College London. All other data was developed and managed by myself and I conducted all analyses with statistical advice from M.P. All authors contributed to the paper. The work was accepted for publication at the Journal *Nature Sustainability* on the 30th of April 2021 (Maes et al., 2021). Additional thanks to R. Gibb and M. Blangiardo for discussion and comments.

The work presented in Chapter 4 was initially informed by a pilot study done by the Master student Emily Northridge which I co-supervised during this pilot study. Although the pilot study informed my work in Chapter 4, the main analyses in Chapter 4 have substantially expanded to focus on integrating cognition and mental health benefits as an ecosystem service into environmental accounting frameworks. The initial pilot study was conducted in collaboration with E.N. and B.M. All analyses were conducted by myself and E.N., and all authors contributed to the paper. The paper is submitted for publication at the journal *UCL Open: Environment* where it is currently published as a preprint, and the preprint is provided in Appendix C (Northridge et al., 2020).

The work presented in Chapter 5 was conducted in collaboration with K.E.J., M.B.T., B.M. and the Environment Analysis Unit at the United Kingdom Department for Environment, Food and Rural Affairs (Defra). The study was

conceived by myself and B.M., and I developed the collaboration with Defra through a secondment at the Environment Analysis Unit. I designed and conducted all analyses with policy advice from B.M. and public servants from Defra. The work was developed into a government report in 2018, was published at the journal *Ecosystem Services* in August 2020, and the government report and published paper are provided in Appendix D (Maes *et al.*, 2020). Additional thanks to A. Johnson, C. Smith and V. Burch from the Environment Analysis Unit at Defra for discussion and comments.

The work in this thesis was supported by funding of the London Natural Environment Research Council Doctoral Training Program (NE/L002485/1). All views expressed in this thesis are my own and not necessarily those of the Defra or any other funder.

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CHAPTER 1

Introduction

1.1. SUSTAINABLE DEVELOPMENT CHALLENGE

Sustainable development was first described in the 1987 Brundtland Commission Report as *'development that meets the needs of the present without compromising the ability of future generations to meet their own needs'* (Brundtland, 1987). The concept is increasingly used in policy contexts on all levels to balance environmental, societal and economic considerations in support of a good quality of life. As part of this challenge, this has led to increased interest on the role of natural ecosystems in urban areas (hereinafter called *'urban ecosystems'* and defined in more detail in section 1.2) to deliver human health benefits and a better quality of life. To date, a lot of knowledge gaps remain to address sustainable development of urban ecosystems, in part because sustainable development has many dimensions which are intertwined. The objective of this thesis is to explore the challenge how to sustainably develop urban ecosystems by addressing a subset of this challenge, focusing on existing scientific knowledge gaps between human health and urban ecosystem exposure, the barriers to integrate this information into urban ecosystem accounting, and use of these outputs in public policy to inform decision-making related to urban ecosystems.

To address this challenge, this also meant I needed to study several academic disciplines as a whole instead of just one academic discipline in complete isolation of other disciplines. This was hard to do because the academic experts involved in my thesis were often part of different academic disciplines, departments or universities, and bridging differences of knowledge, working methods and communication styles was as challenging as the main objective of this thesis. This introductory chapter explains the background to the thesis in terms of the knowledge gaps, the specific aims, objectives and overarching methods

used to address these knowledge gaps, and the overall structure of the thesis. I started with a broad literature review to study the interrelationships between international sustainable development goals and management of urban ecosystems (see section 1.2.1 and Chapter 2 for a more detailed discussion). This was followed by an epidemiological study consisting of approximately 6,600 adolescents to explore the role of urban ecosystems for cognitive development and mental health (see section 1.2.2 and Chapter 3 for a more detailed discussion). Then, I analysed environmental accounting frameworks to explore its feasibility for valuing cognitive development and mental health benefits received from exposure to urban ecosystems (see section 1.2.3 and Chapter 4 for a more detailed discussion). Finally, I did a systematic public policy analysis to understand the relevance, if any, of environmental accounting to broader public sector decision-making across all public bodies in the UK (see section 1.2.4 and Chapter 5 for a more detailed discussion). This mixed-method approach, which includes a systematic review, qualitative and quantitative analyses from different academic disciplines, enabled me to explore the barriers to integrate scientific data and statistics on urban ecosystems into accounting, and use of these outputs in public policy to inform decision-making related to urban ecosystems.

1.2. STATUS OF CURRENT RESEARCH

Urban areas are centres for innovation, culture, commerce and science. The possibility to pursue better socio-economic opportunities within urban areas has been a key driver for global urbanisation trends (UN-Habitat, 2020). More than half of the world's population (~56.2%) now lives in urban areas and this share could increase to 60.4 per cent by 2030 (UN-Habitat, 2020). Urban areas are increasingly recognised to be associated with both positive and negative human health impacts (Vlahov and Galea, 2003), and empirical evidence points that urban residents have better health than their rural counterparts (Ezzati et al., 2018). However, despite the opportunities, the health advantages of living in urban areas is unevenly distributed (Ezzati et al., 2018). Inequality has reached its highest levels in the last 30 years, stigmatising and excluding particular groups of the urban population from society (Stiglitz, 2012; UN-

Habitat, 2020). Climate change risks exacerbate existing challenges such as the urban health island effect and flooding (Beaumont et al., 2011; Gaston, 2010). Some of the worst biological and chemical pollution is seen in rapidly urbanising areas (Landrigan et al., 2017). For example, urban and household air pollution is considered to represent the largest share of pollution-related diseases (Landrigan et al., 2017). Other diseases have been associated with urban lifestyles such as allergies and obesity (Carrillo-Larco et al., 2016; Elholm et al., 2016; Lovasi et al., 2013), while infectious diseases such as tuberculosis, hepatitis and dengue fever easily spreads in densely populated areas, posing a considerable threat to human health and well-being (WHO, 2010).

Urbanisation, by definition, increases pressure on natural ecosystems. Remnant natural environments in urban areas are sometimes referred to as urban green or blue space, green or blue infrastructure, urban natural ecosystems or natural environments. Based on the definition for ecosystems in the Convention on Biological Diversity (UN, 1992a), I define '*urban ecosystems'* in my thesis as natural environments that contain a dynamic complex of both biotic and abiotic components of the natural environment that interact as a functional unit in an urban area. This can include parks, street trees, woodlands, lakes or rivers, amongst other urban ecosystem types. Increasing pressure onto urban ecosystems results in habitat reduction, fragmentation, pollution or contamination, and biodiversity loss (CBD, 2010a; CBO, 2012; Fengxiang et al., 2003; Fischer and Lindenmayer, 2007; Hermansen et al., 2017; Hung et al., 2017). In fact, the impact of urbanisation and associated urban lifestyles onto urban ecosystems and their ecological processes is now regarded as a key impediment to the sustainable development of urban areas (Forman, 2014; Francis and Chadwick, 2013; Gaston, 2010). Meanwhile, an increasing body of evidence shows that ecosystem services provided by urban ecosystems can help manage urban areas through, for example, improvements in water retention and purification (Forman, 2014), mitigation of the urban heat island effect (Akbari et al., 1997; Vaz Monteiro et al., 2016), the creation of biodiversity hotspots (Farinha-Marques et al., 2011) and benefits for human health and well-being (Hartig et al., 2014). Growing political concern about the protection and

management of urban ecosystems is part of a broader concern about the implications of ecosystem degradation. Since the 1992 United Nations (UN) Conference on Environment and Development, ambitious international commitments have been made to address the challenge of sustainable development, which includes issues of ecosystem degradation within urban areas (see 1.2.1. below for detailed discussion) (UN, 1992b).

1.2.1. Global commitments concerning sustainable development

The 1992 UN Conference on Environment and Development was a the first non-binding action plan to achieve global sustainable development by 2000 (UN, 1992b). Since then, sustainable development has been progressively recognised in international political commitments. The 2000 Millenium Summit was the first international commitment by world leaders to develop a set of 8 Millenium Development Goals (MDG) and included practical steps to, amongst others, eradicate extreme poverty and hunger, and ensure environmental sustainability (UN, 2015a). Although successes were made with the MDGs developed, there was a need for a new global agenda on sustainable development (UN, 2015a). In September 2015, the 193 members of the UN General Assembly formally adopted the UN Sustainable Development Goals (SDG). The preamble of the 2030 Agenda recognises the importance of sustainably managing Earth's natural resources, including urban ecosystems, as an important basis for present and future social and economic development. The 2030 Agenda features 17 SDGs and 169 targets that set out global objectives for sustainable development on matters such as climate change, economic growth, poverty eradication and urban development (UN, 2015b). It recognises the importance of urban challenges and SDG 11 is entirely dedicated towards safe, resilient and sustainable cities and human settlements. The 2030 Agenda also highlights that many themes are well connected with each other (Le Blanc, 2015; Waage et al., 2015). For example, climate action has been found to reinforce all 17 SDGs, while a lack of climate action can undermine 16 SDGs, indicating that climate change action and development governance should be better connected (Nerini et al., 2019). Simlarly, sustainable development of urban areas cannot be achieved in

isolation from other themes such as economic growth, equality, discrimination or good governance.

Although many of these international commitments are relevant and applicable to urban ecosystems, there is little reference to urban ecosystems. Only SDG Target 11.7 explicitly mentions urban ecosystems and posits to *'provide universal access to safe, inclusive and accessible, green and public spaces, in particular for women and children, older persons and persons with disabilities'* (UN, 2015b). Translating such a broad and globally focused 2030 Agenda into a specific decision-making context is an important practical challenge for decision-makers in all sectors (ICSU, 2017). A critical knowledge gap exists on the role of broad international commitments such as the UN SDGs to address specific challenges such as sustainable development of urban ecosystems. It is currently unclear what changes in decision-making are required to sustainably develop urban ecosystems. It is equally unclear how urban ecosystem management can reinforce or undermine other themes of the 2030 Agenda for sustainable development, such as SDG 14 (i.e. Life Below Water) and 15 (i.e. Life on Land). Understanding the interactions between urban ecosystems and other SDGs is important, especially considering the possibility that sustainably developing urban ecosystems may require addressing other SDG such as economic growth, good governance or human health, amongst others.

1.2.2. Associations between urban ecosystems and health

Growing evidence highlights the role of urban ecosystems to deliver human health and well-being benefits (WHO, 2021). Based on the World Health Organization's definition (WHO, 1946), I define *'health'* in this thesis as the state of complete physical, mental an social well-being and not merely the absence of disease or infirmity. Urban ecosystems have been associated with a number of improvements to human health such as improvements of local air quality (Gauderman et al., 2015; Kardan et al., 2015; Landrigan et al., 2017; Nowak et al., 2014), physical activity (Coombes et al., 2010; Richardson et al., 2013), social contacts (Kuo et al., 1998), cognition and mental health (Dadvand et al., 2015a; Duarte Tagles and Idrovo, 2012; MacKerron and

Mourato, 2013), and a decrease of stress levels (Roe et al., 2013; Thompson et al., 2012). These human health benefits are also observed in middle-income and low-income countries. For example, park visitation rates in Tabriz (Iran) were positively associated with emotional state and contendness with life, indicating that results corroborate with those found in developed countries (Yigitcanlar et al., 2020). However, health and well-being measures such as measures for cognition and mental health do not lend itself easily to experimental research, making it difficult to determine whether associations with urban ecosystems are causal. Most research agree on the important role played by cognition on mental health, and the urgency to better understand the association between cognition, mental health and urban ecosystems is high (Marin et al., 2011). Mental health problems are one of the main causes of overall disease burden worldwide, and depression was found to be the predominant mental health problem, accounting for 4.3% of the global disease burden (Vos et al., 2015; WHO, 2013). The cost of mental health can also be substantial on a local scale; for example, 1 in 4 Londoners are estimated to experience a diagnosable mental health condition during their lifetime, costing £26 billion annually through poorer education, employment and quality of life, highlighting the urgency to better understand the role of urban ecosystems to cognitive development and mental health (GLA, 2014).

Large epidemiological studies that examine associations between urban ecosystems and measures of cognition and mental health have almost exclusively measured ‘greenness’ through vegetation indices such as the Normalized Difference Vegetation Index (NDVI), a unit-less index of relative overall vegetation density and quality (Amoly et al., 2014; Dadvand et al., 2015a; Engemann et al., 2019; Sarkar et al., 2018). However, this tends to simplify ‘greenness’ without taking into account the types of urban ecosystems that exist. For example, standing and flowing water bodies such as lakes, rivers or reservoirs (hereinafter called blue space), were often excluded from nature and mental health research (Astell-Burt and Feng, 2019; Engemann et al., 2019; Sarkar et al., 2018), and if included, showed significant associations with mental health and cognitive development (Amoly et al., 2014; Barton and Pretty, 2010). In

addition, forests have been proposed to generate a restorative effect both psychologically (Akpinar et al., 2016; Astell-Burt and Feng, 2019) and physiologically (Li, 2010). For example, studies showed that forests have a more restorative effect when compared with overall urban green space, agricultural land or wetland, amongst others (Akpinar et al., 2016; Astell-Burt and Feng, 2019). Although many of these measures to assess environmental exposure have found associations with cognitive development or mental health, to date there is no comprehensive agreement which types of urban ecosystems are more or less important.

Previous studies have assessed a variety of environmental exposures in relation to cognitive development and mental health, but have often focused on adults (Gascon et al., 2015). However, there is growing recognition of the importance of urban ecosystems for children and adolescent's cognitive development and mental health as well (Amoly et al., 2014; Dadvand et al., 2015a; Engemann et al., 2019). Children and adolescents are in in the midst of their cognitive and mental development and nearly half develop first onset of adult mental illness in childhood or adolescence (Kessler et al., 2005), affecting the child, its family and the broader community (PHE, 2016). Approximately 14% of children worldwide suffer from a mental disorder (Polanczyk et al., 2015). On a local scale, 10% of children in London (~111,600 children) between the ages of 5 and 16 suffer from a clinical mental health illness (PHE, 2016). Excess costs of mental health problems in children were estimated between £11,030 and £59,130 annually for each child and included expenditure from conventional medical treatments such as medication and therapy (PHE, 2016). The role urban ecosystems may have on children's cognition and mental health is a subset of the broader challenge to understand how urban ecosystems can reinforce or undermine other SDG themes such as human health (see 1.2.1. above for more detailed discussion). Understanding the value of urban ecosystems for these health benefits may enable urban planners and other decision-makers with evidence to inform future interventions in urban ecosystems (see 1.2.3. below for more detailed discussion).

1.2.3. Valuing health benefits in urban ecosystem accounts

One way to reconsider the value of urban ecosystems is by integrating ecosystem and biodiversity values into (inter)national, regional and local accounting. Natural capital describes those elements of nature that produce value or benefits to people (directly or indirectly), including the natural processes and functions that underpin their operation (NCC, 2013). Valuing natural capital, of which urban ecosystems are a subset, requires understanding what benefits flow from natural capital assets to our economy and society. Just as is the case with produced capital, the value of natural capital can depreciate if it is misused or is overused (Dasgupta, 2021). The benefits derived from natural capital are described as ecosystem services (ES) and are commonly classified into three distinct Sections, i.e. (1) provisioning services which include all physical products that we take from natural capital assets, (2) regulating and maintenance services which maintain environmental processes and sustain the biophysical environment, and (3) cultural services which are the non-material amenities that people gain from interacting with ecosystems (Haines-Young and Potschin, 2018). Valuation of natural capital helps to understand its contributions to society and the economy as a whole, including its contributions to human health and well-being (Stiglitz et al., 2010). Degradation of nature in favour of land uses which produce marketable goods has resulted in a 60% decline in ES productivity compared to 50 years ago, highlighting the urgent need for international and national political commitments to integrate natural capital valuation into standardised accounting frameworks that inform decision-making (GLOBE International, 2014; MEA, 2005).

Since the 1992 UN Conference on Environment and Development, the relevance and importance of natural capital accounting for public sector decision-making about sustainable development has been progressively recognised in international political commitments such as Aichi Biodiversity Target 2 and the UN SDGs (CBD, 2010b; UN, 1992b). For example, SDG target 15.9 calls on all countries, by 2020, to *"integrate ecosystem and biodiversity values into national and local planning, development processes, poverty reduction strategies and accounts"* (UN, 2015b). Similarly, SDG target 17.19 calls on all

countries, by 2030, to *"build on existing initiatives to develop measurements of progress on sustainable development that complement gross domestic product, and support statistical capacity building in developing countries"* (UN, 2015b). These political commitments have led to the development and adoption of a standardised framework for environmental accounting called the UN System of Environmental-Economic Accounting (SEEA) (UN, 2014a). The SEEA is a statistical framework that addresses the need to better account for environmental resources in economic and social accounting. It contains a set of standardised concepts, definitions and accounting rules that link environmental data and statistics to economic accounts (UN, 2014a). It provides a structure that is both standardised and transparent, enabling compatibility with the UN System of National Accounts which is an internationally agreed set of measures of economic activity (UN, 2014a; UN DESA, 2009). However, the contribution of most regulating and cultural ES, as well as certain provisioning ES, are currently not included in the SEEA Central Framework (SEEA CF). The SEEA Experimental Ecosystem Accounting framework (SEEA EEA) and its 2020 revision called the SEEA Ecosystem Accounting (SEEA EA) presents efforts to account for the complete environmental-economic system (UN, 2020, 2014b), but to date ES related to cognitive development and mental health are not included in a standardised framework for natural capital accounting.

The need to integrate ES related to cognitive development and mental health benefits is high. For example, an estimated cost of £370 million due to mental ill-health is avoided each year because of London's parks, while another study showed that Attention Deficit Hyperactivity Disorder (ADHD) medication replacement effects by increasing exposure to urban ecosystems could save between US$383.5 million to US$1.9 billion per year in the United States (U.S.) (Mayor of London, 2017; Wolf et al., 2015). However, inconsistencies within the field of environmental accounting hinder the integration of cognitive development and mental health benefits received from nature exposure into a standardised international framework. For example, different ES classification systems are used around the world such as the Common International

Classification for Ecosystem Services (CICES) developed by the European Environment Agency, and the National Ecosystem Services Classification System (NESCS) developed by the United States Environmental Protection Agency. The CICES considers broad Sections where cognitive development and mental health benefits are considered part of cultural ES (Haines-Young and Potschin, 2018). Meanwhile, the NESCS uses a coding or numbering system to represent the underlying classification structure and currently excludes many intermediate ES including ES related to cognitive development and mental health (Landers and Nahlik, 2013; US EPA, 2015). However, key knowledge gaps within nature and mental health research may also hinder its integration into a standardised international framework. For example, various factors contribute to a person's cognitive development and mental health (see 1.2.2 above for more detailed discussion). Different conceptual models have been proposed that harness existing knowledge by characterising natural features and contact with nature as a means to explain its effect on cognitive development and mental health, while taking into account various factors such as age, gender or socio-economic status (Bird et al., 2018; Bratman et al., 2019; Hartig et al., 2014). Despite the progress to understand the complexity of interactions between nature, cognitive development and mental health, to date there is no transparent standardisation into the SEEA framework.

1.2.4. Mainstreaming urban ecosystems accounts across public policy

Despite the lack of inclusion of ES related to cognitive development and mental health in international environmental accounting frameworks, the SEEA framework is being adopted across the world. Over 80 countries have now compiled or published natural capital accounts following the SEEA CF with 32 countries planning to do so (UNSD, 2019). Although the adoption of the SEEA was a significant achievement in the evolution of international accounting standards, it did not automatically result in its direct application across policy domains. Mainstreaming environmental policies such as the SEEA framework across policy domains is challenging, but important, especially considering the cross-cutting aspect of environmental accounting across policy

domains. Based on the definition from the Global Environment Facility (Harrison et al., 2014), I define *'mainstreaming'* in my thesis as the process that integrates a cross-cutting issue into the development planning or decision-making processes.

Environmental policies integration (EPI) has been widely debated, even though evidence of actual application is rather inadequate particularly for environmental accounting frameworks such as the SEEA (Jordan and Lenschow, 2010; Lafferty and Hovden, 2003). EPI provides an opportunity to prevent environmental damage from occurring. Even though widespread political commitments were made in most industrialised states, disagreement around its day-to-day implementation in decision-making has resulted in differences between countries. Climate adaptation strategies, for example, are increasingly suggested to be mainstreamed across governance because of the growing importance of changing climate. However, operationalisation of climate adaptation mainstreaming is often limited and inconsistent between countries, making it difficult to share good practises (Runhaar et al., 2017). In addition, a lack of political commitment from higher levels fails to institutionalise practises of climate adaptation mainstreaming (Runhaar et al., 2017). Similarly, international environmental accounting standards have been widely adopted around the world (UNSD, 2019). However, it was not automatically adopted across all policy domains, and environmental accounting has mostly been used in traditional environmental policy domains (Vardon et al. 2016). This led to the suggestion for a phased introduction of environmental accounting because it may be better for political and practical reasons (Vardon et al. 2016). However, mainstreaming environmental accounting across governance and other public sector decision-making bodies remains an important practical challenge for decision-makers today, and raises the question: which domains of public sector decision-making are important in a phased introduction of natural capital accounting?

1.2.5. Crossing disciplinary boundaries

In this thesis, I explored ways to sustainably develop urban ecosystems by integrating information across different academic disciplines. For example, environmental health data and statistics related to cognitive development and mental health can form part of the 'information' foundation on which environmental accounts are developed, and in turn these environmental accounts inform broader public policy and decision-making. This process of organising data and statistics into accounts to create a set of associated indicators is called the information pyramid (Figure 1.1). It enables decision-makers to understand the meaning of data and statistics and make evidence-based decisions, connecting science with policy (Hammond et al., 1995). This also implies that to further our understanding of urban ecosystem sustainability, I cannot study one academic discipline in complete isolation of the other. Disciplines are constructs involving distinct objects and methods of study, making it distinctly different from other disciplines, but to date successful cooperation between disciplines remains limited (Petts et al., 2008). Based on the information period, I framed key knowledge gaps of each academic discipline in this thesis, starting with key knowledge gaps of what the international community tells us in terms of sustainable development of urban ecosystem through the UN SDGs and what evidence there is for interrelationships between sustainable development themes (see section 1.2.1 and Chapter 2 for a more detailed discussion). Out of broad literature review emerges a nested hierarchy of knowledge gaps addressing different stages within the information pyramid (Figure 1.1).

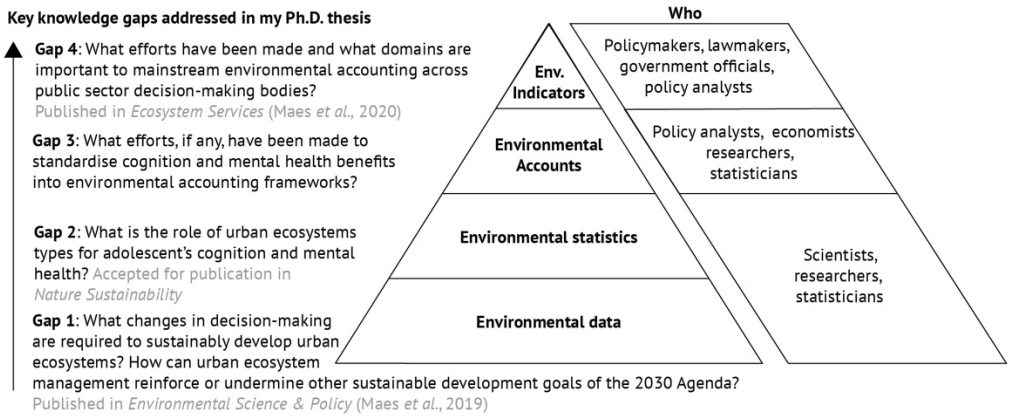


Figure 1.1. Key knowledge gaps addressed in my Ph.D. thesis to address the issue of sustainable development of urban ecosystems by connecting scientific data and statistics with public policy based on the information pyramid (Hammond et al., 1995).

Different types of cooperation between disciplines exist. In a multidisciplinary context, different disciplines come together, but continue to work primarily within their own framing and methods (Petts et al., 2008). In contract, interdisciplinarity involves synthesising the knowledge of different disciplines and occupying the 'space between disciplines' (Petts et al., 2008). Finally, in a transdisciplinary context, traditional disciplinary boundaries are transcended, challenging and renegotiating these disciplines, and sometimes re-drawing the disciplinary map (Petts et al., 2008). To successfully complete this thesis, I needed to understand how each discipline was constructed and how these disciplines would cooperate with one another. This also involved understanding what problems may arise when different disciplines cooperate such as methodological differences between disciplines, divisions related to equal importance and institutional challenges (Petts et al., 2008). For example, British research councils were—just like this thesis' funding—science specific, and focus primarily on integration within their own groups of sciences (Petts et al., 2008). However, interdisciplinary research and associated publications are becoming more embedded within British research councils, which is particularly important for studying urban ecosystems where a variety of disciplines are often concentrated and interact with one another (HEFCE, 2015).

1.3. AIMS AND OBJECTIVES

The main aim of this thesis is to explore the challenge how to sustainably develop urban ecosystems by addressing a subset of this challenge, focusing on existing scientific knowledge gaps between human health and urban ecosystem exposure, the barriers to integrate this information into urban ecosystem accounting, and use of these outputs in public policy to inform decision-making related to urban ecosystems. Keeping this aim constantly in mind and based on current knowledge gaps outlined in this chapter (highlighted in section 1.2.1, 1.2.2, 1.2.3, and 1.2.4 in a cross-cutting way), I started by studying the global sustainable development goals and its interrelationships with urban ecosystem through a broad literature review (see detailed discussion in Chapter 1). Based on the main aim of this thesis and findings from this initial literature review, I studied a subset of the challenge of the main aim by delving deeper into three academic fields—environmental epidemiology, environmental accounting and environmental policy—in an attempt to develop a highly interdisciplinary thesis where all three fields are equally represented for the purpose of advancing the main aim of this thesis. Building on this and the needs of the public sector, I develop three subsidiary aims for this thesis: (1) to explore existing scientific knowledge gaps between human health and exposure to urban ecosystems by studying a subset of human health (i.e. cognition and mental health benefits), (2) to explore the barriers to recognise these health benefits received from urban ecosystem exposure into environmental accounting frameworks, and (3) to understand how these outputs of scientific data and statistics, and accounting frameworks can inform public sector decision-making.

I focus on the following specific objectives:

1. Demonstrate the interrelationships between management of urban ecosystems and the UN SDGs (see section 1.2.1 for a detailed discussion).
2. Assess associations between urban ecosystem types and adolescent's cognitive development and mental health (see section 1.2.2 for a detailed discussion).

3. Analyse the thematic assessment of urban areas from the SEEA framework and associated policy documents with regards to its feasibility for integrating cognition and mental health benefits as an ecosystem service (see section 1.2.3 for a detailed discussion).
4. Understand the relevance of environmental data, statistics and accounting to public sector decision-making by investigating non-environmental objectives across public sector decision-making for associations with natural capital (see section 1.2.4 for a detailed discussion).

1.4. OVERARCHING METHDOLOGY

1.4.1. Case study selection

Through an interdisciplinary lens, this thesis intends to connect scientific knowledge on cognitive development and mental health benefits received by exposure to urban ecosystems with broader public policy and decision-making. The United Kingdom (UK) is known to have made certain progress to account for natural capital across public policy and decision-making (Defra, 2018; HM Treasury, 2018; ONS, 2018), including the London metropolitan area (Mayor of London, 2017, 2015). Furthermore, the London metropolitan area is the most populated area in Europe with an estimated population of more than 14 million people (Eurostat, 2018) but to date has no large studies looking into the associations between humans' cognitive development and mental health benefits received urban ecosystem exposure. Meanwhile, global political commitments for sustainable development (see detailed discussion in section 1.2.1 and Chapter 2) or environmental accounting frameworks such as the SEEA EA framework (see detailed discussion section 1.2.3 and Chapter 4) are relevant and influence public policy and decision-making in the UK and London, especially considering that the UK Government is a UN member and is an active member in the development of these policy frameworks. Recognising the spatial differences between chapters in this thesis, the UK and the London metropolitan area presented a good opportunity to address the research questions outlined in this chapter with a view to providing insights on how to sustainably develop urban ecosystems in other contexts and jurisdictions.

Accessibility of data is an essential consideration when selecting a case study. In 2012, the Study of Cognition, Adolescents and Mobile Phones (SCAMP) was developed, a longitudinal cohort study established to investigate how the cognition and behaviour of adolescents across the London metropolitan area during late childhood and early adolescence may be affected by use of mobile phones and other technologies that use radio waves (Toledano et al., 2018). In addition, the London metropolitan area is home to a number of public sector bodies which work on environmental accounting and broader public policy and decision-making such as the Greater London Authority (GLA) and the UK Department for Environment, Food and Rural Affairs (Defra), amongst others. Health data from the SCAMP study, as well as a richness of environmental datasets across the London metropolitan area and the presence of important public sector bodies contributing to the field of environment allow for the investigation of the research questions outlined in this chapter.

1.4.2. Methods for Interdisciplinary Research

This thesis is supported by an interdisciplinary team of experts that have had a different training with respect to research methods, making discussions and decisions on the overall design and analyses of this research more challenging. I have selected the Methodology for Interdisciplinary Research (MIR) framework to help decide on a set of aims and objectives, and their relationships to one another (Tobi and Kampen, 2018). The MIR allows for a common research aim— to explore how to connect scientific data and statistics on urban ecosystems with broader public policy and decision-making to support sustainable development of urban ecosystems—to be put at the centre of this thesis, despite the diversity of disciplines in this thesis (Tobi and Kampen, 2018). Employing the MIR framework allows for the use of the mixed method approach, integrating disciplines and opting for sequential modules in a mixed method approach (Tobi and Kampen, 2018). By splitting the research into distinct chapters, it recognises the equal contribution of qualitative and/or quantitative methods in the interdisciplinary research design towards the main aim of this thesis (Tobi and Kampen, 2018). The methods selected in this thesis encompass quantitative approaches from environmental epidemiology and

qualitative approaches from environmental accounting and environmental policy to achieve a deeper and richer understanding of the main aim (Bryman, 2016). I set the scene in chapter 2 by exploring how management of urban ecosystems is interrelated to other development domains through a content analysis of the UN Sustainable Development Goals and systematic literature review. Based on the broader findings of chapter 2 on how urban ecosystems can reinforce or undermine other developmental themes, I then investigate a subset of this challenge in depth in chapter 3 using quantitative approaches to explore the association of urban ecosystems for adolescents' cognitive development and mental health. In chapter 4, I use the findings identified in chapter 3 to explore how cognition and mental health benefits can be integrated as an ecosystem service into environmental accounting frameworks using a conceptual analysis. I then use the findings from chapter 4 in chapter 5 to explore how the outputs from chapter 3 and 4 can be mainstreamed across public sector decision-making using qualitative approaches.

1.5. THESIS OUTLINE

This thesis is structured as follows:

In **Chapter 2**, I conducted a systematic analysis of the interlinkages between the UN SDGs and urban ecosystems, which showed a high number of synergies and trade-offs between the ability to conserve and enhance urban ecosystems, and the UN SDGs. This suggests that management of urban ecosystems cannot be fully addressed without addressing other non-environmental challenges, and that crossdisciplinarity is key to sustainable urban ecosystem management.

In **Chapter 3,** I assessed the types of natural environments in an urban setting and used existing data from the Study of Cognition, Adolescents and Mobile Phones (SCAMP) for associations with cognitive development and mental health during adolescence. I showed that natural spaces and in particular woodlands were significantly associated with cognitive development and mental health, while I found less associations with blue space and grasslands. This suggests that the natural environment type in urban setting should not be

treated equally in urban planning decisions linked to adolescent's cognitive development and mental health.

In **Chapter 4**, I conducted an conceptual analysis of the feasibility of international environmental accounting frameworks and associated policy documents such as the UN System of Environmental-Economic Accounting to account for cognition and mental health benefits received from urban ecosystems as an ecosystem service.

In **Chapter 5**, I conducted a systemic analysis of the UK public sector decision-making to understand the impacts of public sector decision-making and natural capital on each other. I showed that a high number of public sector bodies affect and are affected by natural capital, indicating the cross-cutting relevance of non-environmental objectives on natural capital, which includes urban ecosystems. This suggests the need to account for natural capital benefits in policy domains beyond those focused specifically on environmental policy and management.

In **Chapter 6**, I offered a discussion of the key findings and conclusions of this thesis.

CHAPTER 2

Mapping synergies and trade-offs between urban ecosystems and the Sustainable Development Goals

This chapter was published in the journal Environmental Science & Policy and the published paper is provided in Appendix A (Maes et al., 2019).

2.1. ABSTRACT

Global urbanisation has increased pressures on urban ecosystems, resulting in their loss and fragmentation. In September 2015, the United Nations adopted the 2030 Agenda for Sustainable Development which includes 17 Sustainable Development Goals (SDGs) and 169 SDG targets. Environmental sustainability was a key component of the agenda, recognising that social and economic development depends on the sustainable management of Earth's natural resources. Understanding the interlinkages between the broad and globally focused 2030 Agenda and components of the natural environment remain a practical challenge for both researchers and decision-makers in all disciplines. It is unclear how SDG targets relate to urban ecosystems and what evidence base supports these relationships. Here, I examined the SDGs to understand what decision-making changes are required concerning urban ecosystem management and how management of urban ecosystems can reinforce or undermine action to deliver all 169 SDG targets in the 2030 Agenda. I characterised 91 targets requiring further decision-making action in relation to urban ecosystem management. These collectively emphasise the need to sustainably manage nature, provide equal rights to basic services, pursue sustainable economic growth, and strengthen governance and policy development at multiple scales. I identified 102 targets (99 synergies and 51 trade-offs) with published evidence of relationships with better urban ecosystem management, where these changes affect humanity's ability to realise greater welfare and well-being, and

build physical and social infrastructure. These findings highlight that sustainable management of urban ecosystems cannot be achieved without addressing other issues such as economic growth, equality or good governance. Translating these interlinkages into a strategy supported by all actors in society is important for achieving sustainable urban ecosystem management (see Figure 2.1 for the graphical abstract).

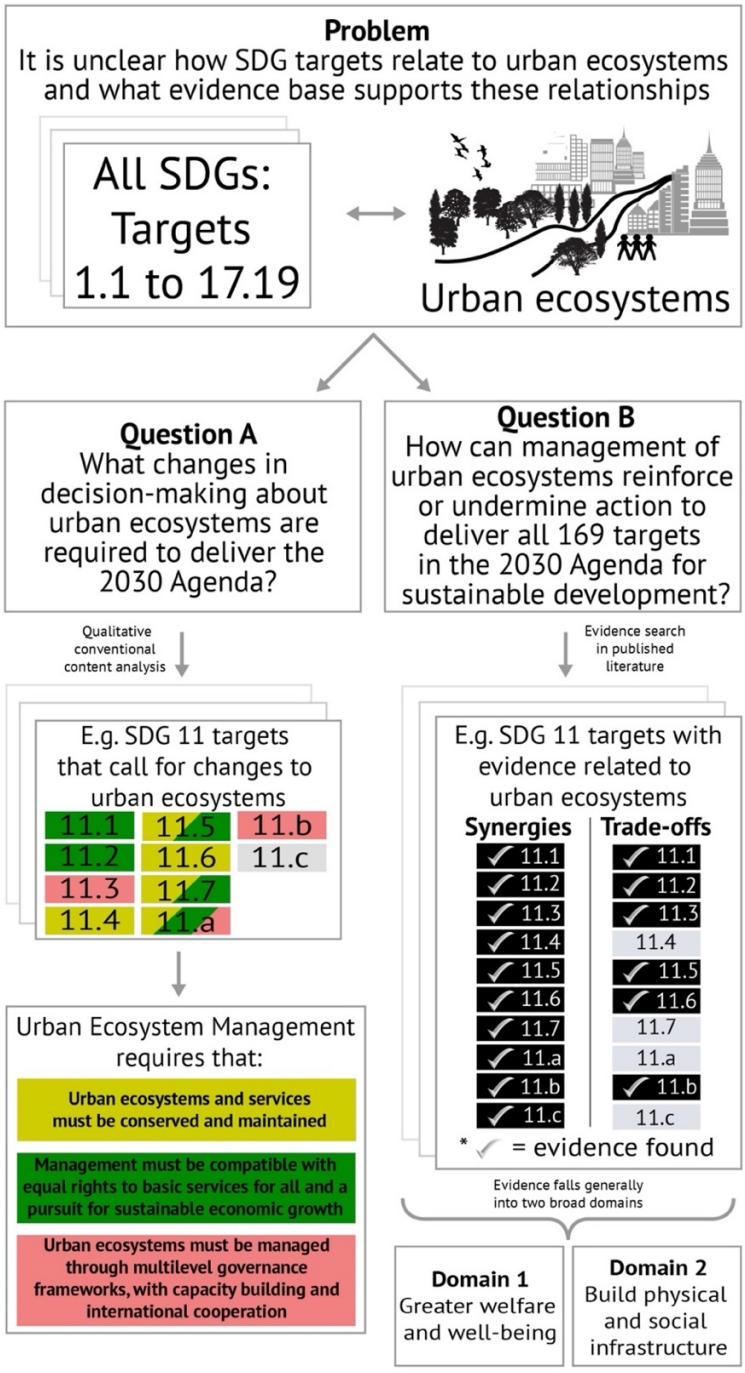


Figure 2.1. Graphical abstract

2.2. INTRODUCTION

Cities are centres for innovation, culture, commerce and science. The possibilities within cities to pursue better social and economic opportunities has been a key driver for global urbanization trends (UN-Habitat, 2016). More than half of the world's population (~54%) now lives in urban areas (UN-Habitat, 2016). This share could increase to ~66% of the global population by 2050 (UN DESA, 2019). Urbanisation has increased pressures on ecosystems, especially those that lie within city boundaries. This has resulted in shrinking green spaces, habitat fragmentation, pollution or contamination of natural environments (Fengxiang et al., 2003; Fischer and Lindenmayer, 2007; Hermansen et al., 2017; Hung et al., 2017) and decline of biodiversity (CBD, 2010a). The impact of urban lifestyles and the built environment on urban ecosystems and their ecological processes is now regarded as a key impediment to the sustainable development of cities (Forman, 2014; Francis and Chadwick, 2013; Gaston, 2010).

An increasing body of evidence shows that components of urban ecosystems can help manage cities through improvements in water retention and purification (Forman, 2014), mitigation of the urban heat island effect (Akbari et al., 1997; Vaz Monteiro et al., 2016), the creation of biodiversity hotspots (Farinha-Marques et al., 2011) and benefits for human health and wellbeing (Hartig et al., 2014). However, associations between urban ecosystems and human health and well-being are not well understood and mostly based on correlative studies without necessarily understanding the causal relationship behind it. An increase in the amount of urban ecosystems has been associated with improvements of local air quality (Gauderman et al., 2015; Kardan et al., 2015; Landrigan et al., 2017; Nowak et al., 2014), increases in physical activity (Coombes et al., 2010; Richardson et al., 2013), improvements in mental health (Duarte Tagles and Idrovo, 2012; MacKerron and Mourato, 2013) and a decrease of stress levels (Roe et al., 2013; Thompson et al., 2012) (see detailed discussion in Chapter 3).

Growing political concern about the implications of ecosystem loss—both within and beyond cities—for social and economic development has prompted

ambitious commitments being made at a global level. The 2000 Millenium Summit launched 8 Millenium Development Goals (MDGs) for the year 2015. Although successes were made (UN, 2015a), there was a need for a new global agenda on sustainable development. In September 2015, the 193 members of the United Nations (UN) General Assembly formally adopted the UN Sustainable Development Goals (SDGs). The preamble of the 2030 Agenda recognises the importance of sustainably managing Earth's natural resources as an important basis for present and future social and economic development. The 2030 Agenda features 17 SDGs and 169 targets that set out global objectives for sustainable development on matters such as climate change, economic growth, poverty eradication and urban development (UN, 2015b).

Translating the broad and globally focused 2030 Agenda into a specfic decision-making context is an important practical challenge for decision-makers in all sectors (ICSU, 2017). Here, I respond to a subset of this broad challenge through a literature review and qualitative content analysis to examine two questions focused on urban ecosystems and their management; (A) What changes in decision-making about urban ecosystems are required to deliver the 2030 Agenda? (B) On the basis of current evidence, how can management of urban ecosystems—in particular investment, conservation, and enhancement of those ecosystems—reinforce or undermine action to deliver all 169 targets in the 2030 Agenda for sustainable development? In this chapter, I define *'decision-making'* as the act or process of deciding something on urban ecosystems with a group of people, while I define *'management'* as the act or process of some intervention on urban ecosystems. I jointly define decision-making and management because these terms are interrelated. Previous analyses have attempted to map environment-human interactions for all SDGs and synthesised relevant evidence and knowledge gaps between each SDG and the environment (Scharlemann et al., 2016). Our analysis builds on this by focusing specifically on only one element of the natural environment (i.e. urban ecosystems) and by giving a more detailed analysis of its implications for future sustainable management.

2.3. METHODS

2.3.1. Normative implications of the 2030 Agenda for management of urban ecosystems

Identification of principles for sustainable development of urban ecosystems entails analysis of the content of the SDGs in order to identify all SDG targets that stipulate action in relation to urban ecosystems. I assessed the normative implications of all 169 targets for their interlinkages with urban ecosystems by answering the following question: Does this SDG target call for action in relation to urban ecosystems (Figure 2.2A)? For example, SDG target 1.4 calls for 'all men and women to have equal rights to economic resources' including natural resources extracted from urban ecosystems. After identifying all SDG targets that call for action in relation to urban ecosystems, these targets were then distilled into a list of core principles for sustainable development of urban ecosystems. A consensus-based qualitative content analysis was undertaken to identify key cross-cutting normative themes concerning the management of urban ecosystems. The qualitative content analysis contained three stages: (1) the wording of all identified SDG targets was individually summarised into a maximum set of three themes which can be either a word or a short sentence, (2) the themes in stage one were once again summarised into a maximum set of three themes for each SDG which again can be either a word or a short sentence, and (3) a final three key themes were identified for all SDGs together based on the themes of stage two. Results and their implications for urban decision-makers are discussed in section 2.4. This analysis was informed by Elo and Kyngäs (2008) and enables us to iteratively summarise the normative content of the SDG targets in a transparent and reproducible way (Harwood and Garry, 2003). This systematic procedure avoids imposing our own value judgement and minimises subjectivity in the analysis of the normative content.

2.3.2. Synergies and trade-offs between urban ecosystem management and sustainable development

To understand how management of urban ecosystems can reinforce or undermine action to deliver all 169 targets in the 2030 Agenda, I identified evidence of empirical relationships (synergies or trade-offs) between action to deliver one target and actions to invest in, conserve and enhance urban ecosystems (Figure 2.2B). I used a consensus-based approach to identify synergies and trade-offs, which involved the search for published studies in peer-reviewed journals or reports published by non-academic organisations (e.g. UN reports) using the Google Scholar search engine. Although the use of the Google Scholar engine has been discouraged, especially for systematic reviews (Gusenbauer and Haddaway, 2020), I chose the Google Scholar search engine because it is considered one of the most comprehensive academic search engines (Gusenbauer, 2019). It includes published studies or reports which were not peer-reviewed, allowing for the identification of relevant literature beyond peer-reviewed academic articles. No uniform set of search terms could be used in this analysis because all SDG targets were investigated, indicating that search terms constantly changed depending on the SDG target studied. These results were refined through facilitated discussions between the four authors of the published paper based on this chapter, which span a diverse range of disciplines from medicine, natural sciences and law until a consensus was reached (Maes et al., 2019, Appendix A). As I do not seek to make a definitive statement on the relationship between urban ecosystems and the SDGs, a single item of published evidence was considered sufficient to indicate the presence, if any, of a synergy or trade-off between the SDG target and urban ecosystems, which otherwise would require a larger systematic literature review. I considered the presense or absence of the interaction only (i.e. whether it is a synergy or trade-off). Weighting the interaction as suggested by Nilsson et al. (2016) is not done here because estimating whether an SDG target is, for example, inextricably linked to the achievement of another goal, or whether it aids the achievement of another goal can be arbitrary. It is also fundamentally impacted by geography,

governance and technology (Nilsson et al., 2016). The analysis was done with an inductive methodology because no prior conceptual or theoretical structure was constructed prior to the analysis.

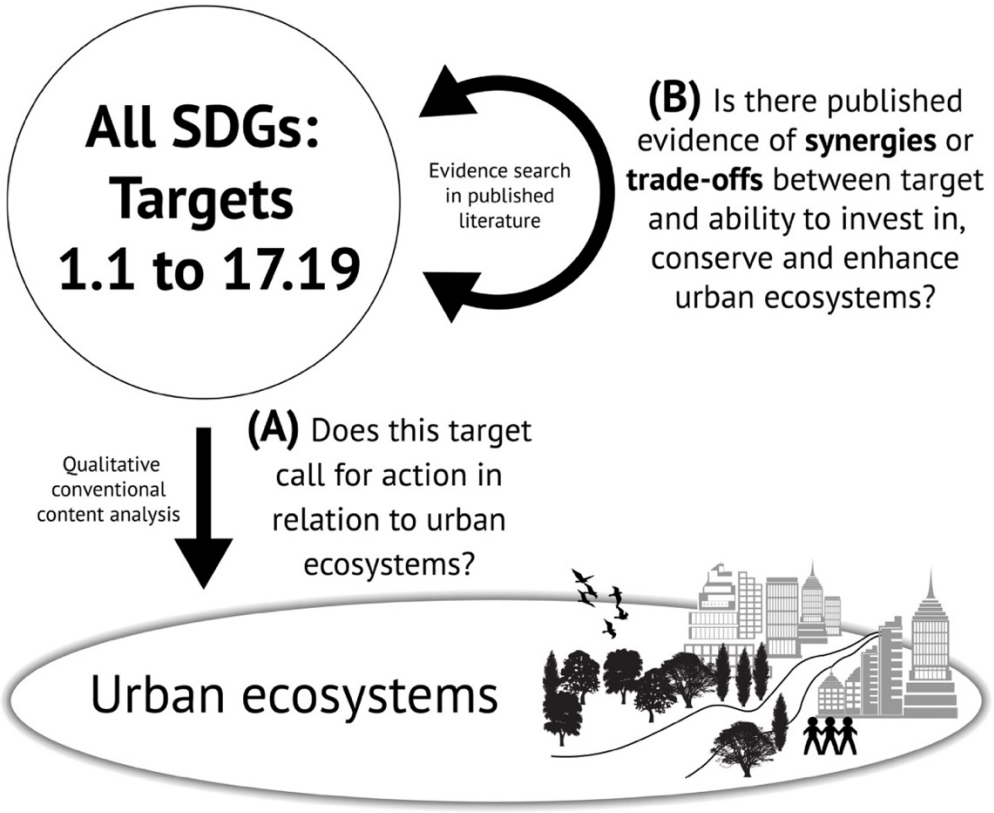


Figure 2.2. Assessing interlinkages between the SDG targets and urban ecosystems.

An illustration of the research questions and methods used for assessing each SDG target in relation to urban ecosystems. (A) What changes in decision-making about urban ecosystems are required to deliver the 2030 Agenda? (B) How can management of urban ecosystems reinforce or undermine action to deliver all 169 targets in the 2030 Agenda for sustainable development?

2.4. NORMATIVE IMPLICATIONS OF THE 2030 AGENDA FOR MANAGEMENT OF URBAN ECOSYSTEMS

I found that 91 targets (54%) call for decision-making in relation to urban ecosystems (Figure 2.3A). This includes a variety of actions such as protecting ecosystems (e.g. targets 14.2, 15.1, 15.5 and 15.7), providing equal rights to different types of services (e.g. targets 2.1, 7.1 and 11.1) and improving governance and cooperation (e.g. targets 13.3, 16.6, 16.7 and 17.9). The qualitative content analysis summarises the diverse range of actions for each SDG (Figure 2.3B) into three key themes to sustainably manage urban ecosystems

by 2030 (Figure 2.3C), i.e. (1) urban ecosystems must be conserved and maintained, (2) management must be compatible with equal rights to basic services for all and a pursuit of sustainable economic growth and (3) urban ecosystems must be managed through multilevel governance frameworks, with capacity building and international cooperation. These key themes give a strong indication of the substantial change needed in other disciplines in pursuit of sustainably managing urban ecosystems. My results were documented in full in Appendix A (Table A.1 and Table A.2).

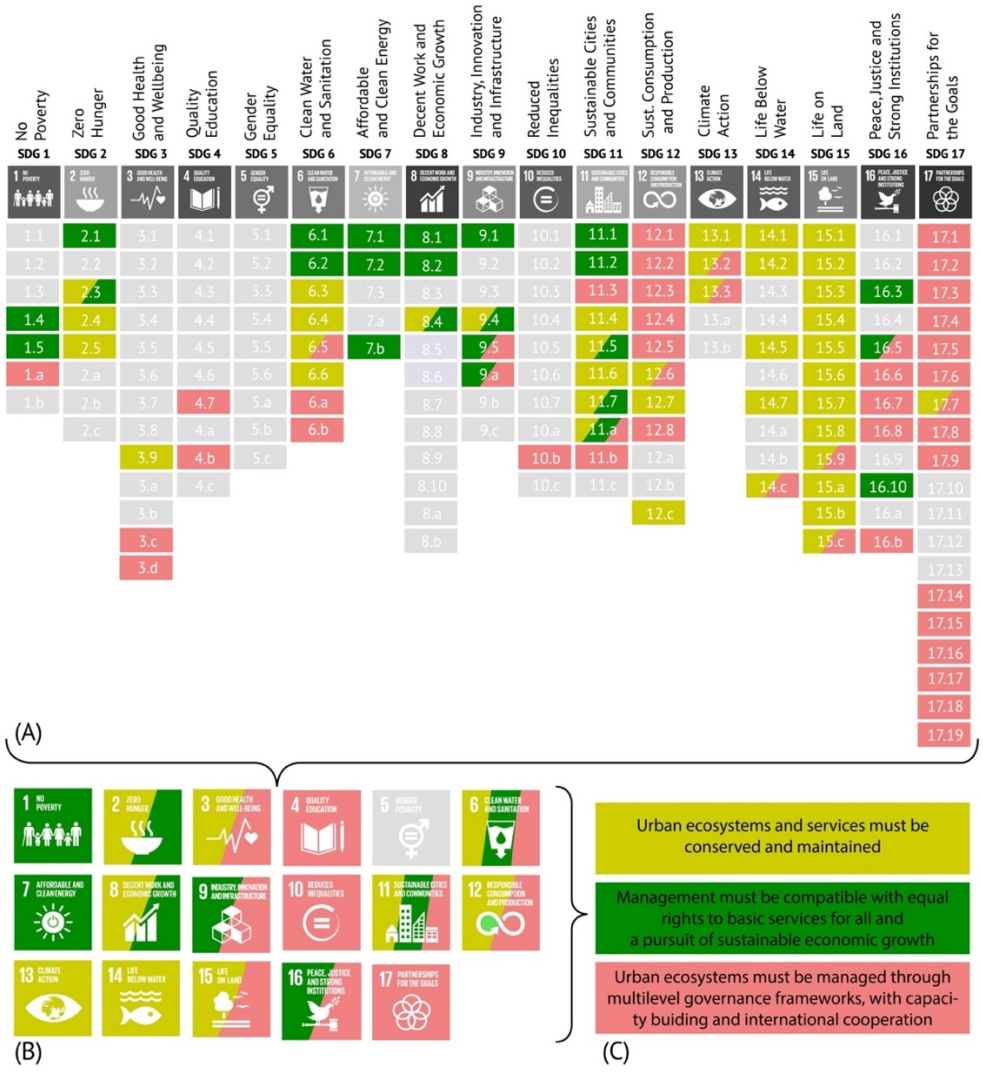


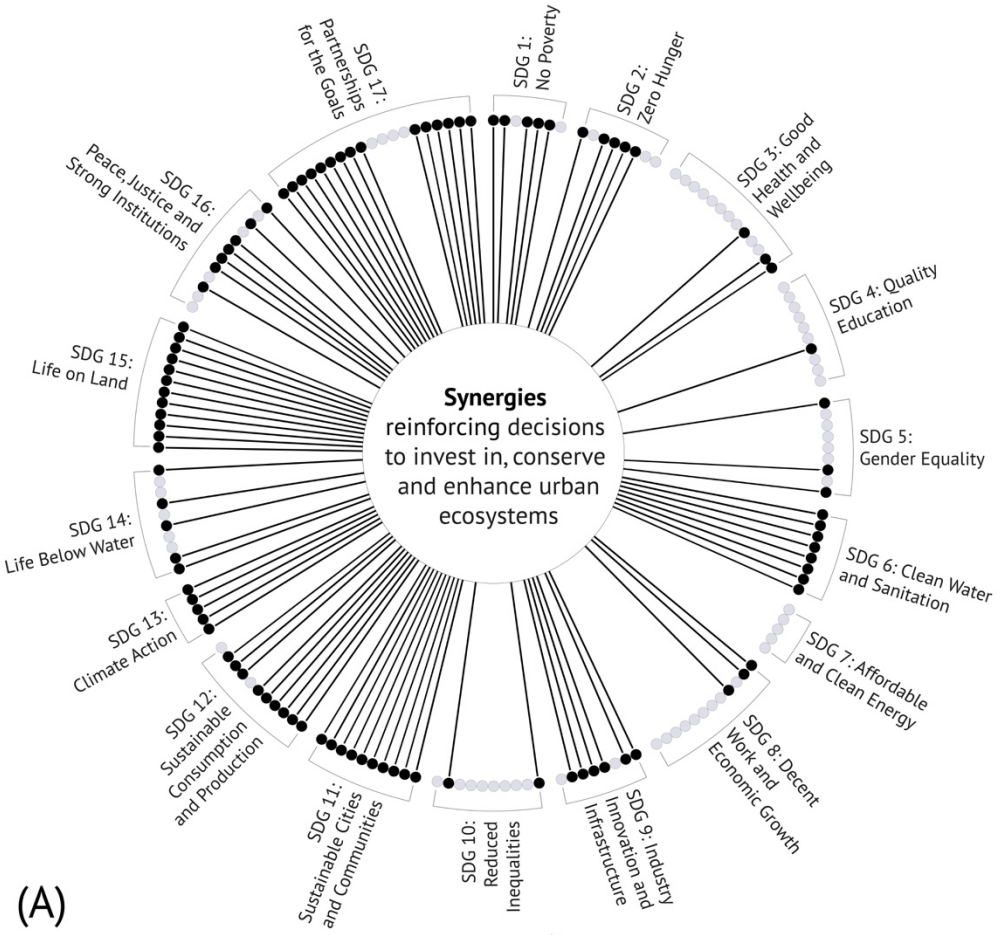
Figure 2.3. Identifying key themes to sustainably manage urban ecosystems.

This figure shows the results of the qualitative content analysis I undertook on all SDG targets that call for actions in relation to urban ecosystems. Yellow, green and red are used to highlight the key themes identified throughout the qualitative content analysis. A mixture of more than one colour indicates that more than one key theme is identified in (A) identified targets, (B) identified SDGs and (C) resulting key themes that call for actions in relation to urban

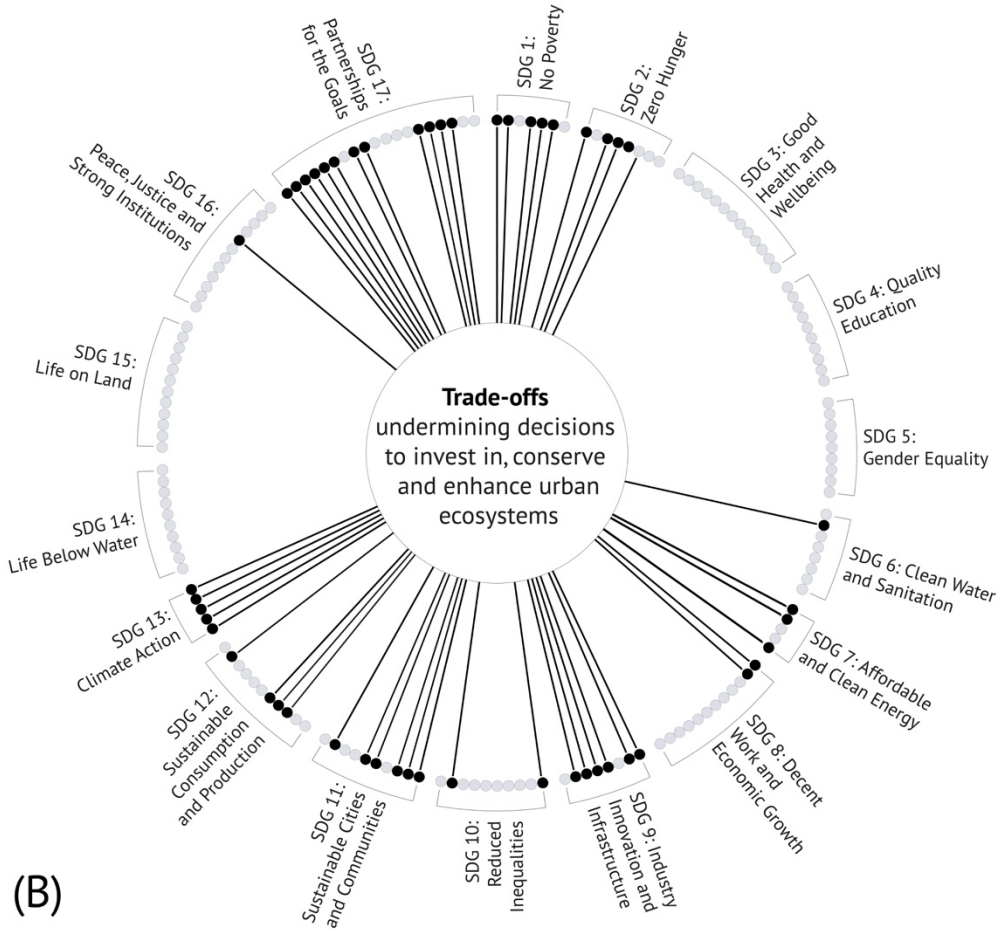
ecosystems. Results from (C) are derived from (B), while results from (B) are derived from (A) in a stepwise qualitative content analysis described in more detail in section 2.3.1. Full results of the assessment for each target can be found in Appendix A (Table A.1 and Table A.2).

2.5. SYNERGIES AND TRADE-OFFS BETWEEN URBAN ECOSYSTEM MANAGEMENT AND SUSTAINABLE DEVELOPMENT

I identified evidence of synergies and trade-offs between 102 targets out of 169 targets (~60%) and actions to invest in, conserve or enhance urban ecosystems. These synergies and trade-offs span all 17 SDGs and cover many different topics relevant to the subject matter of the 2030 Agenda targets such as poverty eradication, economic growth, physical infrastructure and environmental protection. 99 targets out of 169 targets (~59%) were identified to have synergies (Figure 2.4A), while only 51 targets (~30%) were identified to have trade-offs in relation to decisions about urban ecosystems (Figure 2.4B). 48 targets out of 102 identified targets have evidence for both synergies and trade-offs within the target, suggesting these SDG targets can both reinforce and undermine action to invest in, conserve or enhance urban ecosystems. This evidence of synergies and trade-offs falls generally into two domains, where decision-making about urban ecosystems affects our ability to (1) realise greater welfare and wellbeing, and (2) build physical and social infrastructure. Identified evidence within each of these domains is discussed in more detail below.


Synergies
reinforcing decisions
to invest in, conserve
and enhance urban
ecosystems
SDG 1: No Poverty
SDG 2: Zero Hunger
SDG 3: Good Health and Wellbeing
SDG 4: Quality Education
SDG 5: Gender Equality
SDG 6: Clean Water and Sanitation
SDG 7: Affordable and Clean Energy
SDG 8: Decent Work and Economic Growth
SDG 9: Industry Innovation and Infrastructure
SDG 10: Reduced Inequalities
SDG 11: Sustainable Cities and Communities
SDG 12: Sustainable Consumption and Production
SDG 13: Climate Action
SDG 14: Life Below Water
SDG 15: Life on Land
SDG 16: Peace, Justice and Strong Institutions
SDG 17: Partnerships for the Goals

(A)


Trade-offs
undermining decisions
to invest in, conserve
and enhance urban
ecosystems
SDG 1: No Poverty
SDG 2: Zero Hunger
SDG 3: Good Health and Wellbeing
SDG 4: Quality Education
SDG 5: Gender Equality
SDG 6: Clean Water and Sanitation
SDG 7: Affordable and Clean Energy
SDG 8: Decent Work and Economic Growth
SDG 9: Industry Innovation and Infrastructure
SDG 10: Reduced Inequalities
SDG 11: Sustainable Cities and Communities
SDG 12: Sustainable Consumption and Production
SDG 13: Climate Action
SDG 14: Life Below Water
SDG 15: Life on Land
SDG 16: Peace, Justice and Strong Institutions
SDG 17: Partnerships for the Goals

(B)

Figure 2.4. Synergies (A) and trade-offs (B) between urban ecosystems and SDG targets.

Targets are ordered clockwise; for example, target 1.1 is represented by the leftmost circle in the group associated with SDG 1. Targets highlighted in black indicate that published evidence was identified in relation to decisions about urban ecosystems for synergies, or trade-offs. Whereas targets highlighted in grey indicate the absence of identified published evidence. This does not indicate the absence of synergies or trade-offs between that target and decisions about urban ecosystems. Full results of the assessment for each target can be found in Appendix A (Table A.1).

2.5.1. Greater welfare and wellbeing

The availability of well-managed, high-quality urban ecosystems is important for greater welfare and wellbeing. The role of urban ecosystems to this domain is illustrated by 57 targets involving synergies with the ability to invest in, conserve and enhance urban ecosystems. For example, peaceful, transparent and accountable institutions (SDG 16) are important for realising greater welfare and wellbeing. Changes need to be made in governance of urban ecosystems, strengthening the rule of law, reducing corruption, increasing participation at all levels and providing access to information (i.e. SDG targets 16.3, 16.5, 16.6, 16.7 and 16.10) (UNEP, 2012). Our analysis also showed synergies between gender and environment (i.e. SDG target 5.1, 5.a and 5.c). Narrowing gender gaps in agriculture, water and sanitation and other areas has been identified to increase society's productivity (UNEP, 2016). Synergies for good health and well-being are underrepresented in the domain of greater welfare and wellbeing. Only 3 out of 13 targets from SDG 3 were identified to have synergies (i.e. SDG targets 3.9, 3.c and 3.d). Urban ecosystems however, are considered a key-ecosystem based approach offering sustainable and cost-efficient solutions to particular health challenges by increasing physical activity (Hartig et al., 2014; McMorris et al., 2015) and reducing particular air pollutants as discussed in SDG target 3.9 (Nyberg et al., 2000; Tallis et al., 2011; Yang et al., 2008). Bowen and Lynch (2017) reviewed the potential for green infrastructure as an ecosystem-based climate adaptation tool for cities and indicated that there is still considerable debate on the human health benefits of urban ecosystems. Therefore, the evidence base of health and wellbeing benefits from urban ecosystems is limited (see detailed discussion in Chapter 3), and many SDG 3 targets have no published evidence of synergies that relate to subjects known to be connected to issues of the environment (e.g. reducing

maternal mortality, ending the epidemics of AIDS or halving deaths related to road traffic accidents). Together, these explain why our analysis only found limited representation of synergistic responses between good health and well-being and this domain.

Aspirations for greater welfare and wellbeing also has 23 targets involving trade-offs with the with the ability to invest in, conserve and enhance urban ecosystems. For example, eradicating poverty plays a fundamental role in conserving urban ecosystems. Poverty is known to increase pressure on land-use and hinder the conservation of natural ecosystems, especially in cities (Alix-Garcia et al., 2015; Duraiappah, 1998). Raising living standards however, through the provision of basic services such as access to sanitation facilities, energy, and housing services (i.e. SDG target 6.2, 7.1 and 11.1), can change environmental pressures from land-use pressures to increases in pollution (Duraiappah, 1998; Richards et al., 2017; Stern et al., 1996). Therefore, the interlinkages between poverty and urban ecosystems are complex and can have synergies and trade-offs in either direction.

2.5.2. Physical and social infrastructure

Building physical and social infrastructure connects with aspirations to realise greater welfare and wellbeing. Both are underpinned by the natural environment, including urban ecosystems (Waage et al., 2015), highlighting the connectedness between the identified domains and our evidence search in published literature. There is published evidence of 82 targets with synergies between urban ecosystems and actions related to building physical and social infrastructure. For example, Shafik (1994) discussed how access to sanitation and hygiene can reduce environmental pollution, including pollution that would otherwise affect urban ecosystems. Providing access to sanitation and hygiene can therefore be synergetic with the ability to invest in, conserve or enhance urban ecosystems (i.e. SDG target 6.2). Providing access to green and public spaces (i.e. SDG target 11.7) has synergies by creating new green spaces, while reducing social inequalities (Wolch et al., 2014). However, not all greening initiatives provide more equality. Across urban South Africa, for example, public and green infrastructure is more abundant and accessible in

high-income areas compared to low-income areas, suggesting that governance structures are important for having a synergy between access to green and public spaces, and reducing social inequalities (Venter et al., 2020). Other identified evidence showed synergies between waste management and the ability to invest in, conserve or enhance urban ecosystems. For example, Zhao et al. (2011) showed that adequate separation of food waste can result in a more environmentally friendly waste management system. I found no published evidence of synergies for SDG 7 targets (i.e. affordable and clean energy). The absence of identified synergies between SDG 7 and this domain does not imply absence of such evidence for natural ecosystems generally, as there can be synergies that were either not identified in our analysis or are currently understudied.

Evidence of 40 trade-offs were identified between urban ecosystems and building physical and social infrastructure. For example, Sokka et al. (2016) studied the environmental impact of renewable energy targets in Finland and found several environmental impacts of future renewable energy use, even though these environmental impacts are considered to be low. Other identified evidence showed trade-offs between access to affordable housing and the ability to invest in, conserve or enhance urban ecosystems (i.e. SDG target 11.1). For example, Pauleit et al. (2005) showed that urban densification resulted in a loss of green spaces to large extent because of an increase in buildings, including housing development amongst others. Most identified trade-offs are related to land-use changes as expanding physical and social infrastructure can increase pressure on land currently occupied by urban ecosystems such as climate adaptation measures (Fezzi et al., 2015) and energy infrastructure (Hernandez et al., 2014; Sokka et al., 2016). In fact, access to sanitation and hygiene as discussed above can also affect urban ecosystems because of land-use pressures. Many of the targets with identified trade-offs in this domain have an accompanied synergy for that same target. Therefore, a key aspect of this domain is how the natural environment, which includes urban ecosystems, is taken into consideration when building physical and social infrastructure.

2.6. IMPLICATIONS FOR URBAN ECOSYSTEM SCIENCE AND POLICY

My analysis maps the relationships between urban ecosystems and broader development goals of the 2030 Agenda, building on growing political awareness and previous research that many themes are well connected among one another (Le Blanc, 2015; Waage et al., 2015). I revealed that sustainable management of urban ecosystems cannot be achieved in isolation from other issues such as economic growth, equality or good governance. My result is a first attempt to expose the complex relationships between urban ecosystems and the SDGs. It shows that sustainable management of urban ecosystems cannot be achieved without acknowledging the role of human wellbeing, and physical and social infrastructure. I showed that almost all SDGs and 54% of targets call for action in relation to urban ecosystems. This analysis also exposed the need for government structures that account for synergies and trade-offs to incorporate these results in policy decision-making. Organising evidence of synergies and trade-offs can help policymakers and researchers identify pathways that minimise negative interactions and enhance positive ones. I found evidence of synergies between 99 targets and decisions related to urban ecosystems, indicating that 59% of targets are mutually reinforcing of sustainable management of urban ecosystems. I also found evidence of trade-offs between 30% of targets and decisions relating to urban ecosystems. Most evidence of trade-offs identified in this analysis are related to land-use changes.

Our analysis does not identify which synergies or trade-offs are most important in relation to urban ecosystems. Future context-specific analyses of synergies and trade-offs may wish to weight these relative to each other to support planning and decision-making, recognising of course that weighting of these factors is not solely an objective process (Nilsson et al., 2016). Another potential limitation of this chapter is that no process was undertaken with regards to the selection of experts for refining the results through facilitated discussions. Rather, our analysis is intended to serve as a basis to start a discussion on the integration of other disciplines such as poverty eradication or good governance, which until now have not been traditionally on the agenda for

actors involved in the sustainable management of urban ecosystems. Achieving the SDGs is a long and difficult exercise and requires action from all actors in society.

2.6.1. Implications for the research community

Academic institutions need to extend outside classic academic fields to understand how different disciplines interact with each other. As I have illustrated in this analysis, action to manage urban ecosystems is influenced by more than just conservation issues and is interacting with issues such as poverty, governance, economic growth, and health. Encouraging interdisciplinary work related to urban ecosystems requires actors to share data and knowledge with others outside their own academic fields and set up interdisciplinary collaborations. Academic understanding of urban green infrastructure and its inter-relationships with microclimate, nutrient and water household, and human health, amongst others, is insufficient in many disciplines. For example, several studies using dose-response relationships have identified positive associations between green infrastructure and human health (Cox et al., 2017a, 2017b; Shanahan et al., 2016). Whilst there is a broad consensus that green infrastructure provides particular physical and mental health benefits (Coutts and Hahn, 2015; Hartig et al., 2014), there is very limited understanding of how these health benefits are delivered and what mechanisms are responsible to deliver these health benefits (see detailed discussion in Chapter 3). Franco et al. (2017) suggest that specific research is needed focusing on (i) non-visual pathways for delivering health benefits of green infrastructure, and (ii) stronger interdisciplinary work that goes beyond correlational studies to identify causal relationships.

There is no comprehensive understanding of how to incorporate interdisciplinary collaboration related to urban ecosystems into policy structures and deploy it in specific cities or decision contexts. More recently, focus is shifting from ecosystem-based approaches to nature-based solutions (NBS), broadly defined by Raymond et al. (2017) as solutions to societal challenges that are inspired and supported by nature. NBS provide social and economic benefits and costs, and the value of these additional benefits is not well assessed in

current decision-making structures (Raymond et al., 2017). Since city governments highly value decisions based on budget impacts and return on investments (Bowen and Lynch, 2017), an approach that includes social and economic benefits and the costs such as NBS, could provide opportunities in specific decision-making contexts (Maes and Jacobs, 2017). This suboptimal understanding of urban ecosystems is strengthened by the conventional academic silos in which they are operating. To enhance our understanding of the impact of urban ecosystems, we need to break down academic silos, connect different disciplines and actors, and increase the body of research that focuses on a mechanistic understanding of urban ecosystems in relation to humans and society. This can be done for example by linking urban ecosystem research with specific targets and goals, as I have illustrated here.

2.6.2. Implications for policymaking

The SDGs have emphasised that effective protection of urban ecosystems is only possible by addressing other societal challenges such as poverty eradication, sustainable economic growth, and transparent and accountable institutions on all levels. Understanding the interactions between these different disciplines is complex because of the many synergies and trade-offs between targets and SDGs, as I have shown in this analysis. Synergies and trade-offs may sometimes interact as discussed in earlier examples, indicating a need to understand and study the presence of trade-offs between urban ecosystem management and other development goals when compared to synergies. Decision makers in the public and private sector need to break down barriers between different sectors and departments, and enable more integrated policies that account for interdependencies (i.e. synergies and trade-offs) across SDG themes (Le Blanc, 2015). In practice, this implies decision makers need to transform the decision-making process and mainstream environmental considerations into local, national and global urban policymaking. As a response to the growing demand from local, regional and national governments for assistance in sustainable urban policy-making and planning, new bodies were developed by the UN Environment Programme and the UN Human Settlement Programme such as the Green Cities Partnership and the Urban Planning and Design Lab,

which support through technical expertise and financial contributions. For example, the city of Chengdu received international support through the Green Cities Partnership to advance the development of an ecological ring surrounding the city as it was facing urban sprawl because of the lack of natural barriers confining the city.

Mainstreaming environmental considerations in local, national and global urban policy-making also implies transforming how nature is viewed in society from an unlimited, exploitable resource towards a fundamental part of our society on which our economy is built upon (Mace, 2014). One way to reconsider a nation's value and wealth is by integrating ecosystem and biodiversity values into (inter)national, regional and local accounting as called for by the SDGs. Environmental accounting provides an opportunity to understand the economic benefits of green infrastructure to our society (Gregory McPherson, 1992; Vandermeulen et al., 2011) and is included in the UK's 25 Year Environment Plan as a tool for making key choices and long term decisions (Defra, 2018). Environmental data and statistics are the basis for developing environmental accounts, while environmental accounts are used to create a set of environmental indicators (Figure 2.5). This process of organising information, also called the 'information pyramid', enables decision-makers to understand the meaning of data and statistics and make evidence-based decisions, connecting science with policy (Hammond et al., 1995).

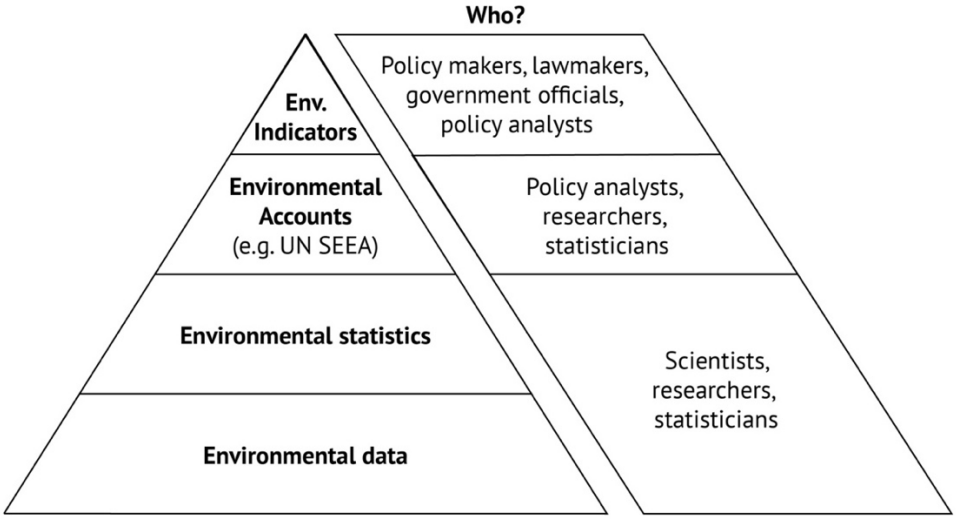


Figure 2.5. The 'information' pyramid shows how information can be organised.

Environmental data and statistics are the basis for developing environmental accounts and indicators, connecting science with policy (Hammond et al., 1995).

The United Nations Statistical Commission adopted a central framework for environmental-economic accounting (UN, 2014b) and other international classifications of ecosystem services have been published (Haines-Young and Potschin, 2018). Accounting for natural capital was expected to figure widely in the UN SDGs (ONS, 2015), and is represented in the UN SDGs through targets 12.6, 15.9 and 17.19. Realising sustainable economic growth requires decision makers to view the environment as a basis of growth. Accounting for natural capital is therefore an important part of determining the 'true' value of the economy and the wider society. Given that urban ecosystems are interlinked with many SDGs and targets (through both synergies or trade-offs), a qualitative analysis, as done here, can help ensure that actions to invest in, conserve and enhance urban ecosystems is in accordance with governance objectives on all levels.

2.7. CONCLUSIONS

Breaking down silos in academic institutions and decision-making bodies, and transforming the process to address societal challenges as discussed here, can only be done if human society changes. Rifkin (2010) discussed the emphatic transformation of humans in the 20th and 21st century, transforming from a small-range, community consciousness towards a global consciousness because of societal changes such as globalisation and the digital revolution. As people's consciousness expands beyond the community to which they are exposed on a day-to-day basis, so does their understanding that everything and everyone is interconnected. People are the driving force of change. Academic institutions can expand our knowledge of the interconnectedness between the SDGs and its targets, decision makers can restructure institutional cooperation, decision-making processes and adapt policy, but all actors need to drive this transformation. One way to facilitate this movement is by creating forums that bring together all actors. Scientists and decision makers cannot develop sustainable solutions without including all actors in society such as NGOs, volunteers and citizen groups. By including all actors in decision processes, a

strategy can be developed to balance out the synergies and trade-offs between urban ecosystems and other important development goals. We translate the challenges we identified in this paper in two steps:

1. Urban research needs to be integrated, reframed and refocused. By addressing academic silo-thinking and making interdisciplinary work standard practise, published evidence will better address the challenge of interlinkages between themes affecting urban ecosystems (i.e. social, environmental, economic and governance challenges).
2. Decision-making needs to account for the published evidence generated from interdisciplinary research. Access and integration of the right information at the right time is important to support policies and decision-making. This can be done, for example, by including the value of urban ecosystems into urban accounts and indicators. A framework that places data and information into the centre of the policy process, also referred to as the Policy Cycle, could facilitate this process (EEA, 2011).

This chapter demonstrates that various SDGs are linked to urban ecosystem conservation. The abovementioned steps are suggested to address the challenge of dealing with evidence of interlinkages. Unfortunately, many benefits provided by urban ecosystems are currently not well understood. Further investigation is required into specific benefits received from urban ecosystems, and how these benefits can be integrated into ecosystem and biodiversity values to make informed decisions about sustainable development of urban ecosystems.

CHAPTER 3

Benefit of urban ecosystems particularly woodland on adolescent's cognition and mental health

This chapter was accepted for publication in the journal Nature Sustainability on the 30th of April 2021 (Maes et al., 2021).

3.1. ABSTRACT

Life in urban areas is associated with various human health effects, including risks of developing cognitive problems and mental health issues. Epidemiological studies have established associations between urban ecosystems, cognitive development and mental health, but why specifically we receive these health benefits remains unclear, especially in adolescents. Here, I used longitudinal data in a cohort of 3,568 adolescents aged 9 to 15 years at 31 schools across London to develop a model and examine the associations between urban ecosystem types, including green and blue space, and adolescent's cognitive development, mental health and overall well-being. I show that, after adjusting for other environmental, demographic and socio-economic variables, higher daily exposure rates to natural space and particularly woodland were associated with enhanced cognitive development and mental health during adolescence. My results suggest that optimising ecosystem services linked to cognitive development and mental health benefits should prioritise the type of urban ecosystem for sustainable urban planning decisions.

3.2. INTRODUCTION

The past decades have seen a tremendous population growth in urban environments and is linked to a number of various human health effects (Giles-Corti et al., 2016; UN DESA, 2019), including risks of developing cognitive problems and mental health issues (Okkels et al., 2018; Robbins et al., 2019). The

negative effects of the COVID-19 pandemic has further exacerbated mental health problems (Holmes et al., 2020; Torales et al., 2020), highlighting the importance to understand the dynamic interactions attributed to higher risk of cognitive problems and mental health issues in urban areas, which until now remain unclear. Emerging evidence suggests that exposure to urban ecosystems plays an important role for cognitive development and mental health (Dadvand et al., 2015a; Engemann et al., 2019; Sarkar et al., 2018). The benefit of urban ecosystems to mental health has been suggested to be comparable in magnitude to family history and parental age, higher than the degree of urbanisation, and lower than parent's socio-economic status (Engemann et al., 2019). Sensory and non-sensory pathways have been suggested as potentially important for delivering cognition and mental health benefits received from urban ecosystem exposure (Cox et al., 2019; Franco et al., 2017; Irvine et al., 2009; Li, 2010; Rook et al., 2012; Weber and Heuberger, 2008). Further research into these pathways will prove fundamentally important to establish a mechanistic pathway between urban ecosystems and mental health.

One of the barriers to understanding associations between urban ecosystems, cognitive development and mental health is the use of inconsistent exposure definitions. Exposure has been measured, amongst others, as physical access to urban ecosystems (Markevych et al., 2014), urban ecosystem type (Akpinar et al., 2016; Taylor et al., 2015), urban ecosystem dose (Cox et al., 2018) and degree of urbanisation (Cox et al., 2018; Engemann et al., 2019). Wider-scale epidemiological research studying the association between urban ecosystems and mental health has almost exclusively measured 'greenness' through vegetation indices such as the Normalized Difference Vegetation Index (NDVI), a unit-less index of relative overall vegetation density and quality (Amoly et al., 2014; Dadvand et al., 2015a; Engemann et al., 2019; Sarkar et al., 2018). NDVI tends to simplify 'greenness' without taking into account the types of urban ecosystems that exist. However, standing and flowing water bodies such as lakes, rivers or reservoirs (hereinafter called blue space) have been associated with mental health and cognitive development (Amoly et al., 2014; Barton and Pretty, 2010). Similarly, forest has been proposed to generate a

more restorative effect both psychologically (Akpinar et al., 2016; Astell-Burt and Feng, 2019) and physiologically (Li, 2010), showing that forests have a more restorative effect when compared with overall urban green space, agricultural land or wetland, amongst others (Akpinar et al., 2016; Astell-Burt and Feng, 2019). To date, there is no comprehensive analysis or agreement which measure of environmental exposure is more or less important.

Many studies have often focused on adult assessments of exposures to urban ecosystems in relation to mental health (Gascon et al., 2015). There is growing recognition of the importance of adolescent's cognitive development and mental health, who are in the midst of their cognitive and mental development (PHE, 2016). In fact, 1 in 10 of London's children and adolescents (~111,600 persons) between the ages of 5 and 16 suffer from a clinical mental health illness and excess costs are estimated between £11,030 and £59,130 annually for each person (PHE, 2016). As for adults, there is evidence that urban ecosystems play an important role in children and adolescent's cognitive development and mental health into adulthood (Bijnens et al., 2020; Dadvand et al., 2015a; Engemann et al., 2019). However, many of these studies tend to exclude or simplify types of urban ecosystems. Nonetheless, particular urban ecosystem types such as blue space or woodlands have been suggested to influence children and adolescent's mental health (Amoly et al., 2014; Milligan and Bingley, 2007), but to date it remains unclear what types of urban ecosystem, if any, influence adolescent's cognitive development and mental health.

3.3. METHODS

3.3.1. Study population

I used data from the Study of Cognition, Adolescents and Mobile Phones (SCAMP), a longitudinal cohort study established to investigate how the cognitive development and behaviour of adolescents across the London metropolitan area might be affected by use of mobile phones and other technologies that use radio waves (Toledano et al., 2018). A first (baseline or t_0) and second (follow-up or t_1) school visit were carried out between 2014 and 2018 with a time gap of approximately 2 years between the first and second visit for each

school. Initially, 6,612 adolescents participated to the first visit, and 5,208 adolescents participated to the second visit. My cohort is an open cohort where adolescents could enter after the first visit, and a total of 3,791 adolescents participated to both the first and second visit. For my analysis, I used a subset of 3,568 adolescents who had a known residence during the first and second visit (Figure 3.1a, Table 3.1). Out of these 3,568 adolescents, 607 (~17%) moved residence between the first and second visit. This subset excluded 8 schools due to low sampling size (< 15 adolescents per school). Included adolescents were on average 12 and 14.2 years old during the first and second visit respectively, and 57.9% of them were female (Table 3.1). The adolescents (n = 3,568) were part of 31 schools across London, of which 12 were independent schools and 19 were state schools. Of the 31 participating schools, 3 were located outside the Greater London Authority (GLA) administrative area (Figure 3.1a). During the assessments, information was gathered on age, gender (two levels: female or male), ethnicity (five levels: White, Black, Asian, mixed or other), school type (two levels: state or independent), parental occupation (five levels: managerial/professional occupations, intermediate occupations, small employers/own account workers, lower supervisory/technical occupations or semi-routine/routine occupations) (Rose et al., 2005), and area-level deprivation (divided in quintiles ranging from category 1 'least deprived' to category 5 'most deprived'). I used the Carstairs deprivation index, an area-level composite measure of deprivation to identify socio-economic confounding (Carstairs and Morris, 1990). The Carstairs index consists of four variables from the UK Office of National Statistics 2011 Census: proportion of low social class, lack of car ownership, household overcrowding and male unemployment (Office of National Statistics, 2012). I categorised the Carstairs deprivation score into quintiles to explore the relative deprivation across areas within which adolescents live. Further characteristics of the study population are presented in Table 3.1 and Appendix Table B.1. All parents or guardians signed the informed consent, and the study was approved (REC reference: 14/NW/0347) by the Health Research Authority NKES Committee North West - Haydock. Study population data are not publicly available for data protection

issues. To request access to the data, contact M. B. Toledano at m.toledano@imperial.ac.uk.

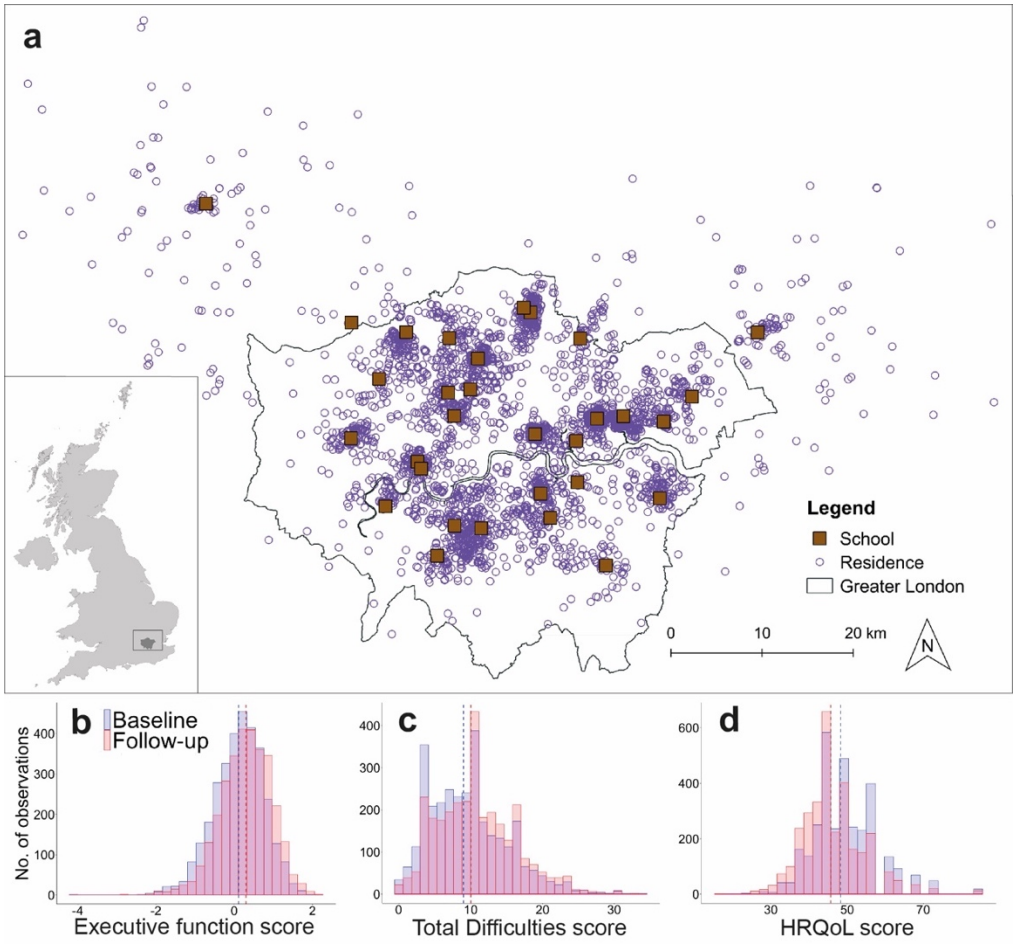


Figure 3.1. Geographic distribution of our study population and associated health variables for cognitive development, mental health and overall well-being.

(a) Residential location during the second (t_1) visit of the 3,568 adolescents with a known residence during the first (t_0) and second visit of the Study of Cognition, Adolescents and Mobile Phones and the 31 participating schools across the London metropolitan area, United Kingdom. Histograms show our t_0 (blue) and t_1 (red) outcome for cognitive development: (b) Executive function score, and our outcomes for mental health and overall well-being: (c) Strengths and Difficulties Questionnaire total difficulties score and (d) KIDSCREEN-10 Questionnaire Health-Related Quality of Life score. A dashed line marks the median (Q_1-Q_3) for our t_0 and t_1 outcomes, i.e. for (b) t_0: 0.16 (-0.30, 0.56), t_1: 0.33 (-0.10, 0.76), (c) t_0: 9 (6, 13), t_1: 10 (7, 14) and (d) t_0: 48.28 (43.34, 53.10), t_1: 45.66 (41.23, 49.76).

Table 3.1. Cohort characteristics of the 3,568 adolescents with a known residence during the first (t_0) and second (t_1) school visit.

Data from t_0 and t_1 were based on participants who took part in the computer-based assessment. Parental occupation is based on the highest National Statistics Socio-economic Classification (NS-SEC) level (five-group version) of either parent. Qn1, Qn2, Qn3, Qn4 and Qn5 of area-level deprivation represented the first, second, third, fourth and fifth quintile of the Carstairs deprivation index, respectively. Full cohort characteristics during t_0 and t_1 are available in Appendix Table B.1.

	n = 3,568	
	Median	IQR
Age (years)	12.96	12.02-14.22
Parental occupation	*n*	%
Managerial/professional occupations	2077	58.21
Intermediate occupations	292	8.18
Small employers/own-account workers	507	14.20
Lower supervisory/technical occupations	161	4.51
Semi-routine/routine occupations	398	11.15
Missing/not interpretable	133	3.72
Area-level deprivation		
Least deprived (Qn1)	580	16.25
Qn2	561	15.72
Qn3	620	17.37
Qn4	747	20.93
Most deprived (Qn5)	1058	29.65
Missing	2	0.05
Gender		
Female	2069	57.98
Male	1499	42.01
Ethnicity		
White	1617	45.31
Black	523	14.65
Asian	959	26.87
Mixed	406	11.37
Other/not interpretable	31	0.86
Missing	32	0.89
Type of school		
State	2556	71.63
Independent	1012	28.36

3.3.2. Outcomes

Adolescent's cognitive development was assessed through a composite score of three computerised executive function (EF) tasks (i.e. Backward Digit Span [BDS], Spatial Working Memory [SWM] and Trail Making Task [TMT]) (Luciana and Nelson, 2002; Tombaugh, 2004; Wechsler, 1944). Versions of these tasks are widely used in EF literature. EF composite was only calculated for adolescents who completed all three contributing tasks. I derived the EF composite at t_0 by taking an average of Z-scores for the key performance measure for each EF task (Burgess, 2004). The composite score at t_1 was

derived by taking an average of scores for the same EF tasks, equivalently adjusted by the mean and SD from the t_0 performance. Z-scores and adjusted values were calculated across the whole population at each time point. TMT and SWM values were reverse coded prior to taking the average. EF values were continuous and higher EF values indicated better cognitive performance (Figure 3.1b).

I assessed adolescent's mental health and overall well-being from the self-reported Strengths and Difficulties Questionnaire (SDQ) and the KIDSCREEN-10 Questionnaire taken by each adolescent (Goodman et al., 2003). The SDQ total difficulties score assesses the emotion and behaviour of adolescents and was calculated by summing the scores for the four difficulties subscales on emotional problems, conduct, hyperactivity and peer problems. Each subscale comprised of five items that can be scored 0, 1 or 2 and each subscale score can therefore range from 0 to 10. An SDQ total difficulties score was treated as count data where a higher value represented more behavioural difficulties (Figure 3.1c) (Goodman et al., 2003). The Cronbach's α for the SDQ in my first and second visit sample was 0.79 and 0.78, respectively, indicating an acceptable internal reliability (Cronbach, 1951).

The KIDSCREEN-10 Health-Related Quality of Life (HRQoL) score consists of 10 self-reported items covering physical, psychological and social dimensions of well-being, with adolescents indicating the frequency or severity of each item on a 5 point Likert scale (1 = never/not at all, 2 = almost never/slightly, 3 = sometimes/moderately, 4 = almost always/very and 5 = always/extremely). Totals of these 10 items were summed with higher values indicating better HRQoL. Rasch person parameters were assigned to each possible total based on the Rasch model, a psychometric model commonly used for measurements of categorical data (The KIDSCREEN Group Europe, 2006). The Rasch-scaled single score of HRQoL was then transformed into scores with a mean of 50 and a standard deviation of approximately 10, where a higher score indicates a better HRQoL (Figure 3.1d) (The KIDSCREEN Group Europe, 2006). The Cronbach's α for the KIDSCREEN-10 Questionnaire in my first and second visit sample was 0.75 and 0.78, respectively,

indicating an acceptable internal reliability (Cronbach, 1951). In line with previous studies, binary cut-offs were applied based on the lower 10% of the sample distribution (i.e. t_0 and t_1 mean below 39.28 and 36.51, respectively) to identify adolescents with noticeably low overall well-being (two levels: 0 - high overall well-being and 1 - low overall well-being) (Berman et al., 2016). All data on adolescent's cognitive development, mental health and overall well-being were gathered using Psytools software (Delosis Ltd., London).

3.3.3. Quantification of urban ecosystem composition

My exposure assessment of urban ecosystems was based on a three-tier stepwise characterisation: (Model I [M I]) natural space, (Model II [M II]) green vs. blue space, and (Model III [M III]) grassland vs. woodland. I used different data sources to quantify the urban ecosystems surrounding the residential and school area of each adolescent. Firstly, I generated a NDVI spatial layer of my study area using data from the Sentinel-2 satellite at 10 m spatial resolution (ESA, 2015). NDVI is a unit-less index of relative overall vegetation density and quality based on differential surface reflectance in the red and near infrared regions (Gascon et al., 2016). It ranges between -1 and 1; generally, moderate values (0.2–0.3) represent shrubs and grassland, while high values (0.6–0.8) indicate temperate and tropical rainforests (Gascon et al., 2016). In my study, I used NDVI values > 0.2 to identify vegetated areas as green space. I generated my NDVI layer by using Google Earth Engine to filter out satellite data between July 1st 2015 and July 1st 2017 for images with less severe cloud cover (<5%) (Gorelick et al., 2017). Images covering the same area at different dates were then mosaicked into a single complete and cloud-free image of NDVI (Appendix Figure B.1a). Secondly, I created a spatial layer from surface and tidal water maps to quantify blue space in my study based on the Ordnance Survey (OS) Open Map, a large-scale digital map covering Great Britain (Appendix Figure B.2b) (OS, 2019).

To further assess fine-scale urban ecosystem types within green space, I used LiDAR data from the Environment Agency (data.gov.uk, accessed July 2nd 2018, licensed under the Open Government Licence 3.0) (Appendix Figure B.1c) (Miura and Jones, 2010). I used the LiDAR Composite Digital Surface

Model and Digital Terrain Model at 2 m spatial resolution to estimate object height across my study area. Within green space, I split vegetation into two height strata: 0 - 1 m and (>1 m), where I assumed that vegetation between 0 - 1 m was predominantly grassland, and vegetation >1 m was woodland (Miura and Jones, 2010).

I calculated each adolescent's proportionate daily exposure rate (DER) to each urban ecosystem characterisation in buffer areas of 50 m, 100 m, 250 m and 500 m around the residential and school area:

$$DER = \frac{(\frac{4RER + 8SER}{12})5 + 2RER}{7} \quad (1)$$

where DER is the daily exposure rate, RER is the residential exposure rate and SER is the school exposure rate. I assumed each adolescent spent the weekend in their residential area, while I weighted weekdays by the daytime (12 hours) adolescents were assumed to spend at home (4 hours) and at school (8 hours). Adolescents who moved residence between the first and second visit had a different DER during t_0 and t_1. I selected different buffer areas to assess the consistency of my results in a comparable manner with previous studies (Amoly et al., 2014; Dadvand et al., 2015a; Engemann et al., 2019). Based on the above formula, I calculated natural space DER by converting and merging my NVDI and water layers into a combined raster layer. Then, I calculated green and blue space DER by using my NDVI and water layers separately. Finally, I calculated grassland and woodland DER by combining my NDVI and height strata layers. The different spatial resolutions of my NDVI and height strata layers resulted in classification errors where pixels were misclassified as grassland or woodland when in fact it was part of the built environment. To correct for this, I excluded buildings from these layers using the buildings feature from OS Open Map (Appendix Figure B.1d) (OS, 2019). It was not possible to use blue space DER of the 3,568 participants because 2,383 adolescents (66.8%) had, for example, no blue space within 250 m. I therefore reclassified blue space into tertiles (three levels: level 1 - no blue space, level 2 - blue space with a DER below the mean, and level 3 - blue space with a DER above the mean).

3.3.4. Quantification of outdoor air pollution

Considering the ability of nature to mitigate local air pollution (Dadvand et al., 2015b), I hypothesised that exposure to air pollution could be an underlying confounder between nature exposure and cognitive development (Sunyer et al., 2015). I did not hypothesise this for my mental health and well-being outcomes because studies on the association between air pollution and these outcomes are still inconclusive (Roberts et al., 2019; Tzivian et al., 2015). I based my exposure assessment of air pollution on emission estimates of key air pollutants using the London Atmospheric Emission Inventory (LAEI) 2016 from GLA and Transport for London (data.london.gov.uk, accessed February 27th 2020, licensed under the UK Open Government Licence 2.0). The LAEI estimated ground level concentrations of four air pollutants (nitrogen dioxide [NO_2], nitrogen oxides [NO_x], and particulate matter with a diameter of 10 microns or less [PM_{10}] or 2.5 microns or less [$PM_{2.5}$]) using an atmospheric dispersion model, and covered Greater London, as well as areas outside Greater London up to the M25 motorway. A total of 3,305 adolescents (out of 3,568 adolescents) were located within the M25 motorway and therefore eligible to measure ambient air pollution. Similar to the characterisation of urban ecosystem types, I calculated each adolescent's average DER to each air pollutant in buffer areas of 50 m, 100 m, 250 m and 500 m around the residential and school area following equation 1. The Pearson's correlation coefficient among DERs ranged from 0.95 (between NO_2 and PM_{10}) to 0.98 (between NO_2 and NO_x) (Appendix Table B.2). To avoid multicollinearity, I used NO_2 DER as it is a commonly used proxy for traffic-related air pollution.

3.3.5. Statistical analyses

My modelling framework consisted of Bayesian longitudinal regression models to account for spatial and temporal correlations. I examined the relationship between urban ecosystem type DERs, and our cognitive development, mental health and overall well-being outcomes. Inference was performed using Integrated Nested Laplace Approximation (INLA) (Rue et al., 2009). The Pearson's correlation coefficient among urban ecosystem DERs ranged from 0.38 (between grassland and woodland) to 0.99 (between natural space and

green space) (Appendix Table B.3). The high Pearson's correlation coefficient was not considered a problem because we performed separated analyses for the different DERs. In particular, I developed three multilevel modelling structures including these as fixed effects, where M I included natural space DER, M II included green and blue space DER, and M III included grassland and woodland DER. My outcomes consisted of two repeated measures per adolescent, i.e. a t_0 and t_1 measure. I assumed a Gaussian, Poisson and Binomial distribution for the EF score, SDQ total difficulties score and HRQoL score, respectively. I included a random effect term for adolescent identifier to allow for between-adolescent variance, while I used a random effect term for tests at the time of visit (two levels: first or second visit) for each adolescent to introduce correlation among the repeated measurements. School was not added as an additional random effect in my multilevel model because it did not improve the model fit, and three different cross-validation techniques were used for model comparison and selection (Appendix Table B.4, Table B.5, Table B.6). I explored the possibility to include a spatial effect, but residual analysis of my fully adjusted models indicated that the data was not spatially clustered using the Moran's I test (Appendix B.7). Fully adjusted models included urban ecosystem type DERs, age, area-level deprivation, ethnicity, gender, parental occupation and school type, and models with the EF score were additionally adjusted for air pollution. Additionally, I did a stratified analysis to investigate potential changes in point estimates and avoid potential bias from over adjustment (four levels: unadjusted, adjusted for ethnicity and school type, adjusted for socio-economic factors and adjusted for all factors) (Appendix Figure B.2, Figure B.3, Figure B.4). A detailed description of the model structures is given in Appendix B Methods 1. Prior to the longitudinal analysis, a cross-sectional analysis of the cohort during the first visit was done which was qualitatively similar to the longitudinal results and is therefore not further discussed (Appendix B Methods 2 and Figure B.5).

We performed the following sensitivity analyses to determine the best models for evaluating the association with urban ecosystem type DER by fitting additional Bayesian mixed-effect models for (i) the association with different

buffer areas (Appendix Figure B.2, Figure B.3, Figure B.4) and (ii) the association with a different weighting of urban ecosystem type DERs based on a full day (24 hours) instead of a daytime (12 hours) weighting where I assumed adolescents spend 16 hours at home and 8 hours at school during the weekdays (Appendix Table B.8, Table B.9, Table B.10). In the main text of this chapter, unless stated otherwise, results were based on fully adjusted models with urban ecosystem type DERs with a daytime weighting and measured in buffer areas of 250 m because I found no strong difference when measuring at different buffer areas, and between daytime or full day weighting. I did all data processing and statistics in Python 3.7.3., ArcGIS 10.7 and R 4.0.0 via RStudio using the packages brinla, ggplot2, ggpubr, R-INLA, MBA, raster, rgdal, sp and spdep (RStudio Team, 2015). All code for processing raw LiDAR data, creating my environmental exposure variables and modelling my data is available at github.com/MikaelMaes/HumanExposure.git.

3.4. RESULTS

3.4.1. The impact of urban ecosystem types on my outcomes

I estimated the change in adolescent's cognitive development, mental health and overall well-being for each type of urban ecosystem by fitting my longitudinal models (Appendix B Methods 1). I found that adolescent's cognitive development improved with higher DER to natural space. When comparing those adolescents exposed to the highest level of natural space (~0.92%) to those exposed to the lowest level of natural space (~0.1%), I estimated a percent change in cognitive development of 2.14% (95% credible interval [CI]: 0.42, 4.29) using the EF score (Figure 3.2a and Appendix Figure B.2a). I also provided the results for the SDQ total difficulties score and HRQoL score with natural space DER (Figure 3.2b,c and Appendix Figure B.2b,c), where I found no improvement of mental health and overall well-being with higher DER to natural space, meaning the 95% CI included the null effect for both models. My M II results for green space DER were almost identical to M I results for natural space DER. This is probably due to a high correlation between our DER for natural space and green space since adolescent's DER to blue space was generally low (Appendix Table B.3). This also meant that my models did

not find an improvement of adolescent's cognitive development, mental health and overall well-being with DER of blue space (Figure 3.2 and Appendix Figure B.3).

To further assess the role of different types of urban ecosystems to adolescent's cognitive development, mental health and overall well-being, I characterised green space into two distinct urban ecosystem types, i.e. grassland and woodland. I found that a higher DER to woodland was associated with higher scores for cognitive development, and a lower risk of emotional and behavioural problems for adolescents. When all other confounding factors were held constant, there was a beneficial contribution to cognitive development by 0.42 (95% CI: 0.21, 0.57) points using the EF score and a reduction in the risk of emotional and behavioural problems by -0.17 (95% CI: -0.32, -0.03) points using the SDQ total difficulties score (Figure 3.2 and Appendix Figure B.4). I found no improvement of overall well-being with higher DER to woodland (Figure 3.2c and Appendix Figure B.4c). When comparing those adolescents exposed to the highest level of woodland (~38%) to those exposed to the lowest level of woodland (0%) in our study, I estimated a percent change in cognitive development of 6.83% (95% CI: 3.41, 9.11) using the EF score, and a percent change in the risk of emotional and behavioural problems of -16.36% (95% CI: -27.49, -3.50) using the SDQ total difficulties score. I found no improvement of adolescent's cognitive development and mental health with a higher DER to grassland with the exception of our outcome for overall well-being using the HRQoL score (Figure 3.2 and Appendix Figure B.4).

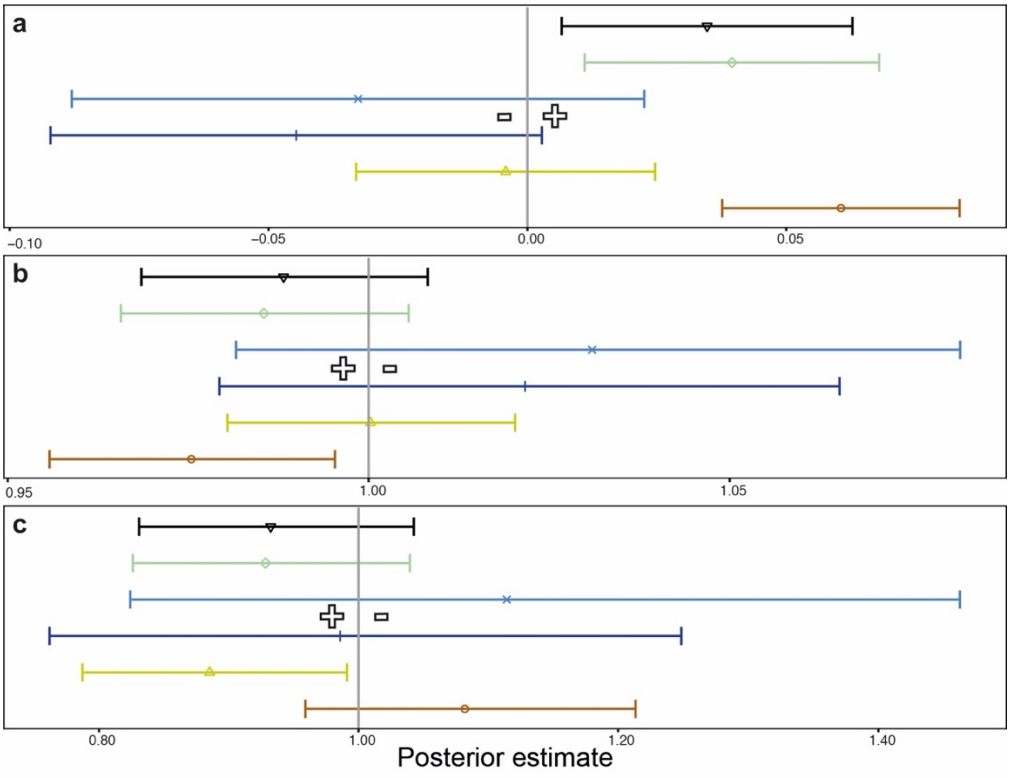


Figure 3.2. Effects and 95% credible intervals (CI) of urban ecosystem type daily exposure rate (DER) with cognitive development, mental health and overall well-being across London.

The association between (a) executive function (EF) score, (b) Strengths and Difficulties Questionnaire total difficulties score and (c) KIDSCREEN-10 Questionnaire Health-Related Quality of Life score with the urban ecosystem type DER of Model I: natural space (▽), Model II: green space (◇), blue space level 2 (×) and blue space level 3 (+), and Model III: grassland (△) and woodland (○). Blue space DER was reclassified into tertiles because 2,383 adolescents (~66.8%) had no blue space within 250 m (Methods). Fully adjusted model was plotted with posterior mean and 95% CI and included age, area-level deprivation, ethnicity, gender, parental occupation and school type. Models with EF as the outcome were additionally adjusted for air pollution. The vertical line (grey) is the reference line and is set to zero or one depending on the model used for the outcome in analysis. Hollow plus or minus signs indicated whether the association had a positive or negative contribution.

3.4.2. The role of confounders in the associations of interest

I fitted my longitudinal models with a number of other factors to account for demographic, environmental and socio-economic factors that are known to influence adolescent's cognitive development and mental health (Afifi, 2007; Guhn et al., 2020). I found that my outcomes for adolescent's cognitive development, mental health and overall well-being were influenced by a variety of other factors such as the adolescent's age, ethnic background, gender, parental occupation and type of school (Appendix Table B.8, Table B.9, Table B.10). When compared to independent schools for example, state schools were predicted to result in a negative contribution to adolescent's cognitive

development, mental health and overall well-being by a percent change decrease of -5.10% (95% CI: -6.05, -4.30) using the EF score, a 10% (95% CI: 5, 15) increase in the risk of emotional and behavioural problems using the SDQ total difficulties score, and an increase in odds of exhibiting low overall well-being by 57% using the HRQoL score (95% CI: 19, 104). I also found that air pollution appears to be unstable in our models, influencing adolescent's cognitive development in some but not all models using the EF score (Appendix Table B.8). When removing demographic, environmental, and socio-economic factors from our models, I showed that modelled environmental variables were, in general, tenfold smaller than the contribution of our demographic and socio-economic variables (Appendix Table B.11). This stepwise exclusion of fixed effects from my models highlights the relative importance of our demographic and socio-economic variables to adolescent's cognitive development and mental health.

To test the robustness of our findings, I did a series of sensitivity analyses to assess which models perform best for evaluating the association between urban ecosystem types and adolescent's cognitive development, mental health and overall well-being. This included testing each adolescent's DER for (i) different buffer areas around their residence and school and (ii) a different weighting based on a full day (24 hours) instead of a daytime (12 hours) weighting. For my analyses of different buffer areas, I found that my results were consistent across different buffer areas but some models did suggest a weaker association with smaller buffer areas when compared with larger buffer areas (Appendix Figure B.2, Figure B.3, Figure B.4). When using a different weighting for my DER, I found that my models showed consistent patterns when I modelled with a DER based on a daytime or full day weighting (Appendix Table B.8, Table B.9, Table B.10).

3.5. DISCUSSION

To my knowledge, this is the largest epidemiological study to report on the impact of urban ecosystem type exposure on cognitive development, mental health and overall well-being during adolescence. My results showed a strong association between woodland exposure, and adolescent's cognitive

development and mental health. I also found that exposure to natural space or green space was associated with a beneficial contribution to cognitive development, while there was a weaker association for my mental health and overall well-being outcomes. Finally, I did not find a consistent association of blue space or grassland exposure with all outcomes.

Overall, I observed that woodland exposure was associated with a beneficial contribution to cognitive development and a lower risk of emotional and behavioural difficulties during adolescence. This is in line with previous reports of woodland's positive impacts on physical and mental health (Akpinar et al., 2016; Li, 2010; Morita et al., 2007), with the exception of a study performed in central Scotland (Thompson, 2017). Forest bathing, for example, is a relaxation therapy that has been associated with physiological benefits, supporting the human immune function, reducing heart rate variability and salivary cortisol, and various psychological benefits (Li, 2010; Morita et al., 2007). However, the hypothetical mechanisms why we experience these psychological benefits from woodland remain unknown. Higher audio-visual exposure through vegetation and animal abundance has been documented to improve mental health, of which both features are expected in higher abundance in woodland (Hedblom et al., 2014; Irvine et al., 2009). Even though my results show that urban woodland is associated with adolescent's cognitive development and mental health, the mechanistic pathway to explain this association remains unknown.

My results also showed that exposure to natural space or green space was associated with a beneficial contribution to adolescent's cognitive development, which was consistent with previous studies (Dadvand et al., 2015a; Liao et al., 2019). My findings of weaker associations between mental health and overall well-being outcomes with exposure to natural space or green space is consistent with the variability in these relationships found in previous studies (Engemann et al., 2019; Markevych et al., 2014; Picavet et al., 2016; Sarkar et al., 2018). It may be that most studies, including this study, do not account for the quality of green space, which has been proposed as more important than the quantity of green space (Francis et al., 2012). Nevertheless, systematic

reviews suggest that nature positively influences mental health; even though, evidence is often limited to cross-sectional studies, and inadequate particularly for adolescents (Gascon et al., 2015).

I did not find a consistent association between blue space exposure, and my outcomes. However, I cannot dismiss that blue space may be associated with my outcomes as other studies have found associations (Amoly et al., 2014; Nutsford et al., 2016). In my study, 66.8% of participants had no blue space within 250 m, showing that the amount of blue space surrounding adolescent's residence and school was low regardless. One explanation for this weak association may be the changing composition of natural environments from one place to the other, potentially changing a person's attachment to nature (Little and Derr, 2020). Residents in coastal cities, for example, may have a different relationship with blue space compared to cities inland where blue space may be less abundant (Bell et al., 2015). Alternatively, inconsistencies may be the result of different sampling techniques. For example, other studies have used self-reported blue space visitation rates or blue space visibility and found associations with behavioural difficulties and psychological distress (Amoly et al., 2014; Nutsford et al., 2016). Inconsistencies due to different sampling techniques make it difficult to harmonize results into a consistent framework, but to date there has been no comprehensive analysis allowing for harmonisation of nature exposure data.

My findings suggested a stronger association with larger buffer areas when compared to smaller buffer areas, indicating that urban ecosystems further away may play an important role for adolescent's cognitive development and mental health. This contrasts with the hypothesis that immediate surroundings may be more relevant for mechanisms of psychological restoration (Amoly et al., 2014), and raises questions on the role of urban ecosystems further away from a residence or school for receiving cognitive development and mental health benefits. At present, conceptual frameworks on nature and mental health discuss proximity to nature as a key component for assessing a person's exposure to nature, but until now it remains unclear at what distance, if any, urban ecosystems become less relevant to a person's cognition or mental

health (Bratman et al., 2019; Hartig et al., 2014). Further research to resolve this critical knowledge gap may prove fundamentally important to understand the pathway through which adolescent's receive cognitive development and mental health benefits from urban ecosystem exposure.

The study has several strengths. It used a high-quality cohort dataset that, to my knowledge, is the largest epidemiological study to report on the impact of urban ecosystem types on adolescent's cognitive development, mental health and overall well-being, a subset of the urban population which is often under-studied. This large sample had substantial spatio-temporal diversity on an urban scale for the London metropolitan area with sufficient statistical power to investigate interactions. The study used clinically validated instruments to define adolescent's cognitive development, mental health and overall well-being. Previous studies have used satellite remote-sensing data for establishing associations between green space, cognitive development and mental health. In this study, I developed a quantitative measure of exposure by combining satellite, Light Detection and Ranging (LiDAR) and other data as a proxy for characterising urban ecosystem types. This includes geographical data of high resolution to develop measures of urban ecosystem DER such as NDVI at 10 m resolution and LiDAR data at 2 m resolution. This study also adjusted for other potential confounders through objective measures of air pollution exposure, socio-economic status and other individual-level factors.

Despite of my large sample size using a rigorous longitudinal study design, my results could be influenced by a number of potentially confounding factors. For example, I cannot necessarily assume that adolescent's DER to urban ecosystems leads to increased use of urban ecosystems as the quality of natural environments may also play a role (Amoly et al., 2014; Francis et al., 2012). My data also did not provide information on when exactly adolescents moved to a new residence between the first and second visit, which may influence our DER measure. I also showed that modelled environmental factors were, in general, tenfold smaller than the contribution of other factors, indicating that increasing urban ecosystem exposure may not be sufficient to improve adolescent's cognitive development and mental health. Additionally, a

considerable proportion of our participants (58.21%) were considered part of the group whose parents had the highest professional occupation, indicating adolescents in less favourable socio-economic groups may be underrepresented in this study (Appendix Table B.1). Added to this, unmeasured factors such as crime rates may also influence my results (Tarling and Roger, 2016). I also wanted my study to be generalisable to the majority of schools in the UK, but I do not exclude that pupils attending special schools, pupil referrals and secure units may be differently affected compared to the general school-age population of the UK. Finally, although my study importantly sheds light on the role of urban ecosystem types for cognitive development and mental health, it also highlights the gap in understanding the mechanistic pathway why we receive benefits from woodland over other urban ecosystem types.

3.6. CONCLUSION

My study showed that higher levels of woodland were associated with a beneficial contribution to cognitive development and a lower risk of emotional and behavioural problems during adolescence. These findings contribute to our understanding of urban ecosystems as an important protective factor for adolescent's cognitive development and mental health. Ensuring fair and equitable access to woodland could be an important tool to manage and minimise cognitive development and mental health problems, especially in adolescents who are in the midst of their development into adulthood. Lower access to woodland may also be an added risk factor among more vulnerable groups in society. This chapter does not establish a causal effect between woodland exposure and cognition and mental health benefits, acknowledging that particular factors (e.g. housing prices) may not have been accounted for in the models developed in this chapter. My findings contribute to our understanding of the physical and monetary valuation of cognitive development and mental health benefits received from urban ecosystems, suggesting that not every urban ecosystem type may contribute equally to these health benefits. As part of the growing human health and nature research, my study concludes that understanding people's local relationship with nature may be a key component to understand its association with cognitive development and mental health. This

should be considered as part of ongoing efforts to sustainably develop urban ecosystems and to standardise international measurement and environmental accounting frameworks for cognitive development and mental health benefits.

CHAPTER 4

Integrating cognition and mental health benefits as an ecosystem service into environmental accounting reveals key gaps

The pilot study which initially informed the analyses in this chapter was submitted for publication at the journal UCL Open: Environment where it is currently published as a preprint and is provided in Appendix C (Northridge et al., 2020).

4.1. ABSTRACT

There is a growing interest in the use of ecosystem accounting to quantify the value of ecosystem assets and services. In this context, there is limited discussion on the integration of cognition and mental health benefits of urban ecosystems into environmental accounting and more specifically, into urban ecosystem accounts. Here, I analysed current environmental accounting standards and associated documents including the thematic accounting for urban areas in the United Nations (UN) System of Environmental-Economic Accounting – Ecosystem Accounting (SEEA EA) framework using a conceptual analysis to show that key gaps remain to integrate cognition and mental health benefits as an ecosystem service into urban ecosystem accounts. Specifically, I found that to better address this challenge (1) knowledge gaps in evidence related to cognition and mental health benefits need to be addressed, (2) better and context-specific data on urban areas and more specifically urban ecosystems needs to be collected such as land cover, and (3) that existing conceptual models need to be adapted to include the use of other factors including the built environment, demographic and socio-economic factors. My results are framed within the broader discussion of the ongoing evolution of the SEEA framework to include ecosystem services which are currently not incorporated into standard

economic reporting and analyses. Combined action by researchers, policymakers and other actors to integrate cognition and mental health benefits into wider environmental accounting frameworks can inform future decision-making and management of urban ecosystems and nature more broadly.

4.2. INTRODUCTION

The costs of cognitive issues and mental ill health to the economy and society as a whole are substantial. The cumulative global impact of mental health conditions between 2011 and 2031 was projected to amount to US$16 trillion, but costs associated with mental ill health can also be substantial on a national and regional level (Bloom et al., 2011). For example, in England, the aggegrate cost of mental health problems was calculated to be US$135 billion (or £105.2 billion) in 2009/10 (Centre for Mental Health, 2010). In Greater London alone, mental ill health costed an estimated US$34 billion (or £26 billion) each year through spending on health and social care, benefits to support people living with mental ill health, costs to education services, the criminal justice system, reduced productivity and reduced quality of life (GLA, 2014). Economic costs of mental ill health have been measured, amongst others, as antisocial behavior (Bogar and Beyer, 2016), consultations and pharmaceutical treatments (Corazon et al., 2018), lost workplace productivity (Brown, D. K. et al., 2014) and staff costs (Buckley et al., 2019). Considering the substantial costs related to cognitive issues and mental ill health to the economy and society as a whole, finding ways to address these costs may be of concern to decision-makers on all levels of governance.

There is broad recognition that exposure to urban ecosystems and natural space more broadly influences cognition and mental health in humans independent of other demographic and socio-economic risk factors (see detailed discussion in Chapter 3; Dadvand et al., 2015; Duarte Tagles and Idrovo, 2012; MacKerron and Mourato, 2013; Maes et al., 2021; Roe et al., 2013; Thompson et al., 2012). The impact of the natural space is thought to be mediated by a number of factors: (1) the size, type or quality of natural features, (2) the proximity, duration or frequency of exposure, and (3) experience features such as types of interaction or different levels of attention,

preference or feelings of personal connection (Bratman et al., 2019; Hartig et al., 2014). Empirical studies which have examined the impact of nature exposure to cognition and mental health, have used a number of different ways to measure exposure including proximity to nature (Markevych et al., 2014; McCormick, 2017; Nutsford et al., 2013), natural habitat type (see detailed discussion in Chapter 3; Akpinar et al., 2016; Astell-Burt and Feng, 2019; Barnes et al., 2019; Maes et al., 2021; Velarde et al., 2007; Wheeler et al., 2015), nature dose (Cox et al., 2018; Shanahan et al., 2016, 2015) and degree of urbanization (Cox et al., 2018; Engemann et al., 2019), amongst others. Meanwhile, cognition and mental health have been measured as reduced depression and blood pressure (Sarkar et al., 2018; Shanahan et al., 2016), improved attention (Amoly et al., 2014), cognition (Dadvand et al., 2015a), sleep (Shin et al., 2020), and stress recovery (Thompson et al., 2012), amongst others. Although there is broad evidence of an association between mental health and nature exposure, such associations have not yet provided conclusive evidence of an underlying causal effect.

Experimental designs have indicated a stress-reducing effect when immersed in urban parks and forests compared to urban built environments, suggesting a causal effect (Hedblom et al., 2019; Tyrväinen et al., 2014) and supports my findings showing that higher levels of woodland were associated with a beneficial contribution to cognitive development and a lower risk of emotional and behavioural problems during adolescence (see Chapter 3 for a more detailed discussion). These findings partain particularly to urban areas where a higher pace of life and social stress create a higher relative risk of developing a mental illness compared to rural areas, where a lower, but signficant, relative risk is found (Engemann et al., 2019). However, small sample sizes and methodological weaknesses suggest evidence for a causal association is currently inconclusive (Mygind et al., 2019), making it challenging to transform these data and statistics into key indicators to inform decision-making.

Efforts to address this challenge have been supported by international environmental accounting frameworks such as the United Nations (UN)

System of Environmental-Economic Accounting Central Framework (SEEA CF) (UN, 2014a), a statistical framework of concepts, definitions and accounting rules that links environmental data and statistics to economic accounts (UN, 2014a). In this chapter, I use the term 'environmental accounting' as an umbrella term covering efforts to use an accounting framework in a systematic way to report on stocks and flows of natural capital, but I acknowledge other terms are used to describe this such as 'natural capital accounting', 'environmental-economic accounting' or 'inclusive wealth accounting'. Within the SEEA CF framework for environmental accounting, the contribution of many regulating and cultural ecosystem services, as well as certain provisioning ecosystem services, were not well recognised. The SEEA Experimental Ecosystem Accounting framework (SEEA EEA) presented efforts to account for the complete environmental-economic system (UN, 2014b), and these efforts have now been renewed by the revised SEEA Ecosystem Accounting (SEEA EA) framework which has now been adopted by the UN Statistical Commission (UN, 2021). It provides a systematic and comprehensive set of descriptions and examples for assessing ecosystem accounts and associated indicators, including its focus on ecosystem assets ('the stock') such as the extent and condition and ecosystem services ('the flows') (Figure 4.1). Part of the challenge is to account for specific environmental themes such as urban areas, and this is now included in the newly adopted SEEA EA framework (see SEEA EA Chapter 13.6) (UN, 2021; UN DESA, 2019).

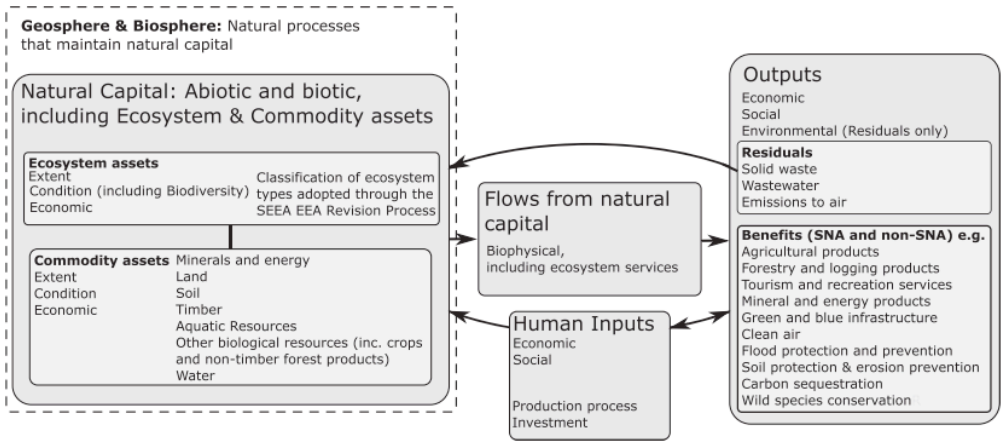


Figure 4.1. A conceptual framework with all key components for environmental accounting: ecosystem assets (extent and condition), flows (services), human inputs and outputs in the form of benefits and residuals (Figure from Fairbrass et al., 2020).

Attempts have been made to estimate the monetary gains related to cognition and mental healing when increasing exposure to nature. A cost-benefit analysis, for example, estimated that Attention Deficit Hyperactivity Disorder (ADHD) medication replacement effects by increasing exposure to urban nature could save between US$383.5 million to US$1.9 billion per year in the United States (U.S.) (Wolf et al., 2015). Similarly, improving natural views in school cafetarias can improve secondary school performance and implies 114,813 additional high school graduates per year in the U.S., resulting in an additional US$1.3 billion in average total annual income for that group (Wolf et al., 2015). In London, economists developed a natural capital account for London's parks, and estimated that London's parks avoided US$473 million (or £370 million) of costs each year related to mental ill health (Mayor of London, 2017). To date, it remains unclear whether these cost-benefit assessments are indeed accurate and whether certain 'natural' treatments or therapies provide added benefits when compared to traditional pharmaceutical treatments or psychological therapies.

Widly-varing montary estimates does raise the question whether these cost-benefit assessments are indeed accurate. In my previous analysis, I showed that woodland improves cognitive development and mental health, while other types of urban ecosystems such as blue space or grassland had less strong associations with these health benefits (see detailed discussion in Chapter 3; Maes et al., 2021). This suggests that the type of urban ecosystem may play a role with regards to cognitive development and mental health benefits (Maes et al., 2021) and is something which is currently unaccounted for in these cost-benefits assessments. In addition, traditional mental health expenditure already enters national accounts but have the shortcoming that it may capitalise into other factors such as housing prices, highlighting the danger of double-counting in national accounts. Therefore, cognitive and mental health benefits received from the human-nature interaction are complicated, and translating data and statistics on cognition and mental health into standardised environmental accounts and indicators is needed to improve cost-benefits assessments and inform decision-making. Here, I examined scope gaps and

definitional issues of current environmental accounting standards and associated documents using a conceptual analysis to assess its suitability for integrating cognitive and mental health benefits as an ecosystem service into an urban ecosystem account by (1) reviewing whether existing global and national ecosystem type classification systems are suitable for assessing urban ecosystems and its delivery of cognitive and mental health benefits, (2) reviewing whether existing concepts and definitions for assessing ecosystem condition aligns with the need to include other factors for making meaningful predictions of cognition and mental health, and (3) analysing whether ecosystem services classification systems allow integrating of cognitive and mental health benefits as an ecosystem service.

4.3. METHODS

The SEEA framework, which includes the SEEA CF, SEEA EEA and SEEA EA is the key international framework that sets the standard for environmental accounting worldwide based on a similar accounting structure as the System of National Accounts (UN, 2021). For this reason, the SEEA framework, and especially the newly adopted SEEA EA are a key policy document analysed in this chapter (Table 4.1). However, a few other policy documents were analysed in this chapter because these documents are used around the world for a variety of reasons. For example, the Common International Classification for Ecosystem Services—developed by the European Environment Agency— and the National Ecosystem Services Classifications System—developed by the United States (US) Environmental Protection Agency—are commonly used classification structures for classifying ecosystem services used by countries beyond Europe and the US (Table 4.1) (Haines-Young and Potschin, 2018; US EPA, 2015). Therefore, it was based on the global relevance that I analysed several national and international policy documents to assess the suitability of environmental accounting frameworks for integrating cognitive development and mental health benefits as an ecosystem service into urban ecosystem accounts and associated indicators (Table 4.1). As indicated earlier, the key document I focused on for this analysis was the SEEA EA framework because the SEEA framework is the key international policy framework that sets the

standard for environmental accounting worldwide based on a similar accounting structure as the System of National Accounts (UN, 2021). The SEEA framework is the most influential policy document related to environmental accounting, with more than 100 countries around the world having developed programmes to apply the SEEA CF, and more than 50 countries having developed programmes to apply the SEEA EEA framework (UN, 2018).

Through a review analysis, I examined scope gaps and definitional issues with current environmental accounting standards and associated documents, focusing on the feasibility to integrate cognition and mental health benefits into environmental accounts and more specifically, into urban ecosystem accounts. The analysis was done through an inductive methodology because no prior conceptual or theoretical structure was constructed prior to the analysis. This analysis was developed through facilitated discussions with my supervisors which span a diverse range of disciplines from medicine, natural sciences and law. In addition, this analysis was informed by consultations with experts from a variety of disciplines spanning environmental economics, urban ecosystem management and national accounting and statistics. Therefore, no specific sampling approach was implemented for the selection of experts in this chapter. Instead, experts were identified because of existing collaborations with these experts and because they are internationally recognised experts in their respective fields coming from a variety of organisations including the UK Department for Environment, Food and Rural Affairs, Yale University and the Greater London Authority. I did not exclude the possibility that other national or international environmental accounting policy documents that were not reviewed in this chapter may have case studies for integration of cognitive development and mental health benefits into urban ecosystem accounts. In the sections below, I report my findings for integrating cognition and mental health benefits into urban ecoystems accounts (including ecosystem extent [see section 4.4.1], ecosystem condition [see section 4.4.2] and ecosystem services [see section 4.4.3]) and associated indicators (see section 4.4.4.).

Table 4.1. Citation and description of the reports reviewed to assess the suitability of environmental accounting frameworks for integrating cognition and mental health benefits as an ecosystem service.

Citation	Description
Haines-Young and Potschin, 2018	The Common International Classification for Ecosystem Services was developed by the European Environment Agency to standardise ecosystem services if ecosystem accounting were to be developed and comparisons made.
Keith et al., 2020	The International Union for Conservation of Nature developed the Global Ecosystem Typology as a hierarchical classification system for defining ecosystems. This report describes the three upper levels of the hierarchy.
UK NEA, 2014	The United Kingdom (UK) National Ecosystem Assessment was the first analysis of the UK's natural environment and provides a national classification system for defining ecosystems in the UK.
UN, 2021	The United Nations (UN) System of Environmental-Economic Accounting: Ecosystem Accounting framework was officially adopted by the UN on March 11th 2021 and includes thematic accounting for urban areas.
US EPA, 2015	The National Ecosystems Services Classifications System was developed by the United States Environmental Protection Agency to serve as a framework for analysing how changes to ecosystems impact human welfare.

4.4. IMPLICATIONS FOR URBAN ECOSYSTEM ACCOUNTING

4.4.1. Ecosystem extent

A key component for developing urban ecosystem accounts is to define the urban ecosystem accounting area, which can be based on administrative boundaries (e.g. local government boundary), functional boundaries (e.g. transportation or trade flows) or morphological criteria (e.g. extent of build-up area) (UN, 2021). However, options for defining the urban ecosystem accounting area depend on the purpose and use of the account. The primary spatial units within an ecosystem accounting area are called ecosystem assets, and each ecosystem asset can be classified to an ecosystem type, reflecting a distinct set of biotic and abiotic components and their interactions (UN, 2021). Contrary to natural ecosystems outside urban areas, urban ecosystems often consist of a mosaic of different ecosystem types, making it difficult to assign a particular ecosystem type to each ecosystem asset.

The general recommendation within the SEEA EA framework to classify ecosystem assets into ecosystem types is to use existing national and subnational

ecosystem classification schemes. National and subnational ecosystem assessments are preferred compared to global ecosystem assessments because it incorporates local ecological knowledge. In the United Kingdom (UK), for example, the UK National Ecosystem Assessment (NEA) captures the diversity of ecosystem types in eight Broad Habitat types, and each Broad Habitat is divided further into sub-habitats (UK NEA, 2011). One of these Broad Habitats is specific for urban areas called *Urban* and has a sub-habitat called *Built Up Areas and Gardens* (UK NEA, 2011). Thus, the UK NEA recognises that urban areas are a distinct ecosystem type with its own set of biotic and abiotic components and their interaction. However, this separate classification also tends to simplify urban areas when in fact urban areas can have a more complicated composition. Urban ecosystems, for example, may consist of a single ecosystem type such as an urban forest, but may also consist of a mosaic of different natural environments, making it problematic to assign one particular ecosystem type.

In cases where a national ecosystem classification is not available, a global ecosystem typology may be used according to the SEEA EA framework such as the International Union for the Conservation of Nature (IUCN) Global Ecosystem Typology (GET) (Keith et al., 2020). Using a global ecosystem classification such as the IUCN GET can also be used to cross-compare between national ecosystem accounts in case that is the purpose or use of the ecosystem account being developed. The IUCN GET has a biome called *Intensive land-use systems* and within this biome, there is an ecosystem functional group called *T7.4 called Urban and industrial ecosystems* (Keith et al., 2020). In a way similar to the UK NEA, the IUCN GET tends to simplify urban areas. Previous analysis in Chapter 3 showed that woodland had a beneficial contribution to cognitive development and mental health during adolescence while other urban ecosystem types such as blue space or grassland were less strongly associated with these health benefits (see Chapter 3 for a more detailed discussion and Akpinar et al., 2016). This suggests that optimising ecosystem services linked to cognitive development and mental health benefits may want to prioritise the type of urban ecosystem. Ecosystem classification systems

such as the UK NEA and IUCN GET are not context-specific for urban areas and may therefore not be meaningful classifications systems for urban areas, particularly for assessing ecosystem services linked to cognitive development and mental health.

The SEEA EA framework acknowledges the ecosystem classification problems for urban areas by developing two main approaches for classifying urban areas into subtypes: (i) a landscape approach or (ii) an individual asset approach (see SEEA EA Chapter 13.6.2) (UN, 2021). The landscape approach disaggregates the urban area and categorises these in larger patches with common characteristics, classifying these according to distinct urban sub-types (e.g. compact high-rise, compact low-rise, open low-rise, sparsely built, paved) (UN, 2021). The individual asset approach tracks various individual ecosystem types to the finest possible scale, and allows for identification of urban ecosystems within urban areas that provide ecosystem services (UN, 2021). Choosing between the landscape and individual asset approach may have considerable implications when developing an urban ecosystem account, especially when estimating cognitive and mental health benefits as ecosystem services. As discussed in Chapter 3, accounting for cognitive and mental health benefits as an ecosystem service requires identifying features of ecosystem assets such as the size, type or quality (Akpinar et al., 2016; Amoly et al., 2014; McCormack et al., 2010). Similarly, identifying exposure features such as proximity, duration or frequency of exposure to distinct urban ecosystems for the purpose of assessing cognitive and mental health benefits requires spatial data sets of high resolution (Shanahan et al., 2015). Based on this scientific knowledge, the individual asset approach is considered more appropriate for integrating cognition and mental health benefits into urban ecosystem accounts compared to the landscape approach.

Despite the need for datasets of high resolution to measure ecosystem extent through, for example, the individual asset approach, there is a considerable lack of available data sources (Northridge et al., 2020, Appendix C). Together with other experts, I explored whether exisiting publicly available data sources for urban areas can be used to develop an inclusive urban ecosystem account

(Northridge et al., 2020, Appendix C). We found that it was currently not possible to compile an inclusive urban ecosystem account consistent with the SEEA framework because of issues with (i) temporal inconsistencies, (ii) public access to data sources and (iii) urban land cover classification (as discussed earlier in this section where existing ecosystem classification systems are not context-specific for urban areas) (Northridge et al., 2020, Appendix C). Renewed effort to address the lack of available data sources will be important to integrate cognition and mental health benefits into urban ecosystem accounts.

4.4.2. Ecosystem condition

Measuring ecosystem extent such as the urban ecosystem size per type of asset is the first step for building a broader urban ecosystem account (Figure 4.2a), but other features of ecosystem assets need to be measured to make meaningful predictors of cognition and mental health effects as an ecosystem service. There is increased recognition that the ecosystem condition of urban ecosystems is important for delivering ecosystem services linked to cognitive development and mental health benefits but it remains unclear what contribution this makes (Amoly et al., 2014; Francis et al., 2012). Several indicators that measure ecosystem condition have been suggested to affect cognitive development and mental health such as the quality of urban ecosystems or the level of biodiversity (Francis et al., 2012; Fuller et al., 2007). Humans, for example, are hypothesised to respond positively to increased levels of biodiversity. One study showed that the species richness of urban ecosystems increases psychological benefits (Fuller et al., 2007), while others argue that it is the biodiversity perceived by humans that shows a positive relationship with species richness (Dallimer et al., 2012). Further research is needed to conclude whether ecosystem condition indicators such as species richness or abundance should be integrated in urban ecosystem accounts assessing cognitive development and mental health as an ecosystem service (Figure 4.2b).

Other factors beyond indicators of ecosystem condition may affect cognitive development and mental health but to date it is unclear how these are framed within the SEEA EA framework. For example, accessibility and availability of

facilities in urban ecosystems have also been suggested as important indicators as humans are more likely to use these urban ecosystems and which could therefore affect cognition and mental health (McCormack et al., 2010; Wood et al., 2017). However, accessibility and availability of facilities are not characteristics of the ecosystem assets being studied, but rather characteristics of the built environment surrounding and embedded within these ecosystem assets. These built characteristics could be considered as part of the 'built condition' and are defined as anthropogenic landscape characteristics that combined with the ecosystem condition may affect cognition and mental health (Figure 4.2c).

Demographic and socio-economic factors have also been associated with human cognitive development and mental health and should be properly accounted for when assessing these benefits as an ecosystem service. This includes, for example, age, ethnicity, gender or socio-economic status, amongst others (Afifi, 2007; Guhn et al., 2020; Maes et al., 2021). Similarly, contact with nature such as frequency or duration of nature visits have demonstrated positive associations with mental health, and conceptual models have integrated these as a necessary part for measuring mental health effects as an ecosystem service (Bratman et al., 2019; Cox et al., 2017a). However, these are not characteristics of the ecosystem assets being studied, but rather characteristics of the human exposed to the ecosystem assets. These human characteristics are part of the 'human condition' and are defined as individual-level characteristics of each human exposed to urban ecosystems (Figure 4.2d).

Existing conceptual models of nature, cognition and mental health are inherently heuristic. Adapting these to account for other factors to make meaningful predictors of cognition and mental health effects as an ecosystem service requires including a myriad of other factors that are not part of ecosystem assets (e.g. built and human condition indicators as discussed above). However, the Convention on Biological Diversity posits that ecosystems are *'a dynamic complex of plant, animal and micro-organism communities and their non-living environment interacting as a functional unit'* (CBD, 2010b). Within this broad legal definition, this suggests that the built and human condition may be

subsets of the ecosystem condition. To date, ecosystem condition indicators for biotic components of the ecosystem assets are well emphasised within the SEEA EA framework, while other factors that are important to make meaningful predictions of cognition and mental health benefits are not well integrated into the SEEA EA framework. For example, the SEEA Ecosystem Condition Typology for organising data on ecosystem condition characteristics focuses only on the condition of ecosystem assets, while it does not discuss the condition of other assets such as the built or human condition (SEEA EA Table 5.1) (UN, 2021). However, the SEEA EA framework posits that *'condition indicators that are predictors of urban ecosystem services should be selected'* (UN, 2021). This suggests that a revision of existing conceptual models for cognition and mental health benefits as an ecosystem service, and the SEEA Ecosystem Condition Typology to include other factors may be required.

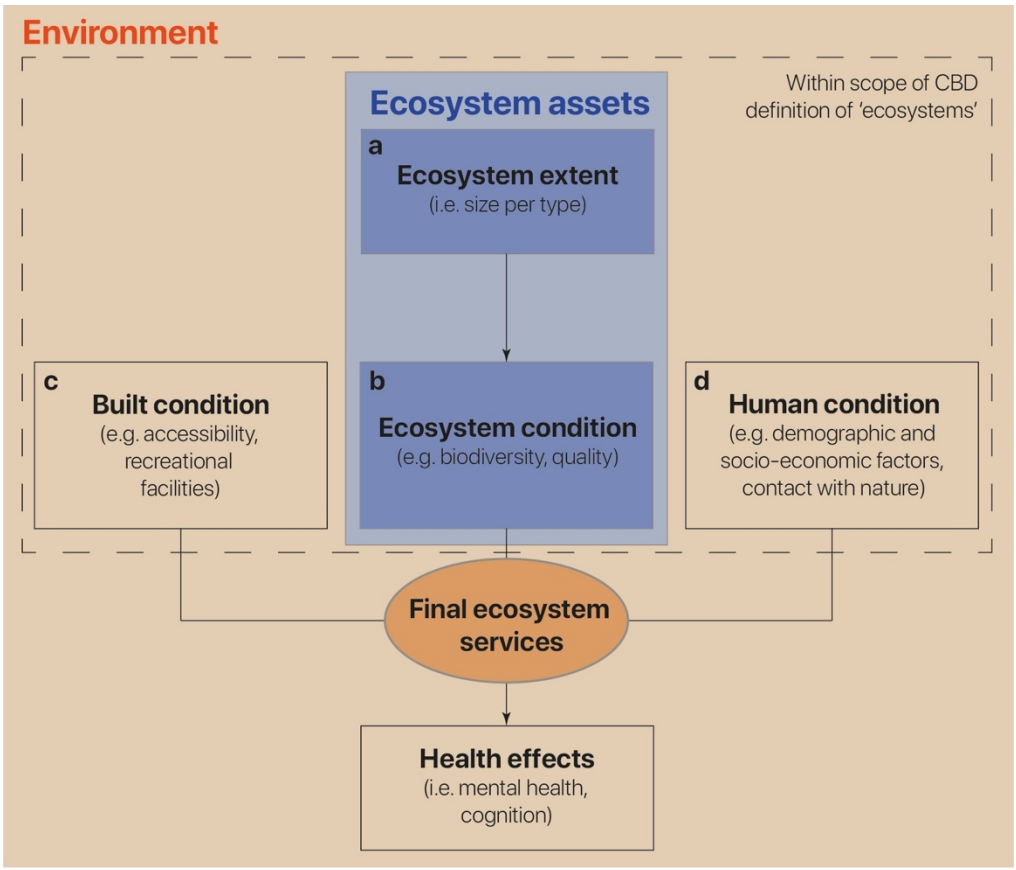


Figure 4.2. A conceptual model for cognition and mental health benefits as an ecosystem service.

(a) Ecosystem extent features include the characteristics of urban ecosystems (size, type) considered in the urban ecosystem account. (b) Ecosystem condition considers the abiotic and biotic ecosystem characteristics, and landscape level characteristics as described in the SEEA

Ecosystem Condition Typology such as the level of biodiversity or the quality of urban ecosystems. (c) Built condition accounts are anthropogenic landscape characteristics such as accessibility of urban ecosystems or presence of recreational facilities. (d) Human condition accounts are inherently unique individual-level characteristics such as demographic factors (e.g. age, gender, ethnicity), socio-economic factors (e.g. individual socio-economic status, area level deprivation) or contact with nature which can include both exposure (e.g. proximity, frequency and duration of contact) and experience sub-characteristics (e.g. experience, dose) (Bratman et al., 2019). Cognitive and mental health effects are the combined result of ecosystem extent, ecosystem condition and a myriad of other factors and are represented here conceptually by the human and built condition, but I do not exclude that other factors may be missing here. This figure is a simplified illustration of the interaction between ecosystem assets and health effects and may not include all mediating/moderating effects. It is based on the conceptual model developed in Bratman et al., 2019. CBD = Convention on Biological Diversity (CBD, 2010b).

4.4.3. Ecosystem services

International and national efforts were made to classify ecosystem services through, for example, the Common International Classification of Ecosystem Services (CICES) and the National Ecosystem Service Classification System (NESCS) (Haines-Young and Potschin, 2018; US EPA, 2015). Notwithstanding that considerable advances have been made, to date there is no internationally agreed classification of ecosystem services (Haines-Young and Potschin, 2018; US EPA, 2015). Based on the work of the CICES, NESCS and other ecosystem services classification systems, the SEEA EA framework generally classified contributions from the environment into three key contributions: (a) ecosystem services, (b) abiotic flows and (c) spatial functions (Figure 4.3) (UN, 2021).

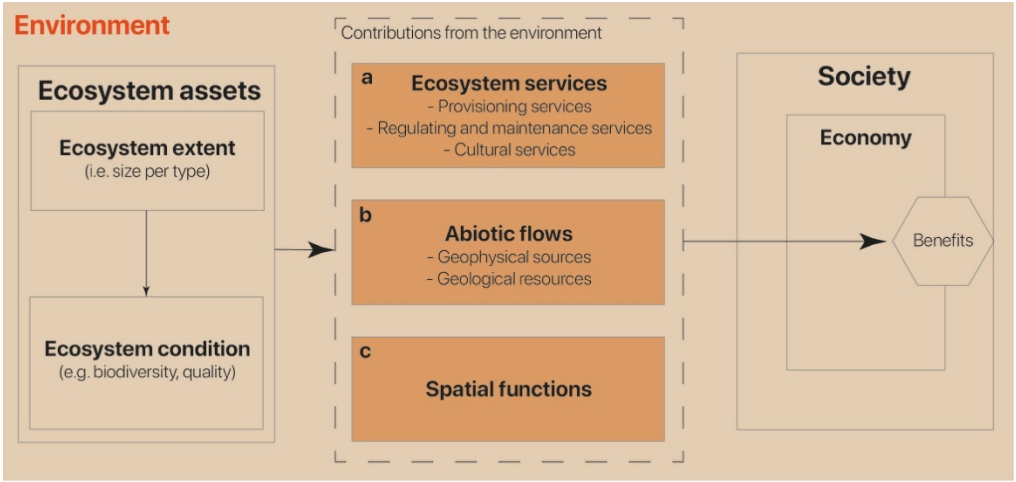


Figure 4.3. A conceptual framework of the contributions from the environment to society and the economy.

(a) Ecosystem services are underpinned by various ecological characteristics and processes. Ecosystem services are generally classified into three classes: provisioning services,

regulating and maintenance services and cultural services, and are distinctly different from (b) abiotic flows which encompass the abstraction and extraction of resources from the environment including through geophysical sources (e.g. abstraction of water, capture of wind or solar) and geological sources (e.g. extraction of fossil fuels, minerals or sand). (c) Spatial functions are contributions resulting from the use of the environment as (i) a location for transportation and movement or (ii) a sink for pollutants and waste (UN, 2021).

Within the SEEA EA framework, cognitive and mental health benefits are considered part of cultural ecosystem services, which are defined as *'the experiential and non-material services related to the perceived or realized qualities of ecosystem assets whose existence and functioning contributes to a range of cultural benefits derived by individuals'* (SEEA EA Chapter 6 in UN, 2020). However, within the domain of cultural services, cognitive and mental health benefits may be classified within several cultural ecosystem service classes. For example, the SEEA EA framework has several ecosystem services within the reference list that may support cognitive and mental health benefits such as recreation-related services, visual amenity services or spiritual, symbolic and artistic services (Appendix Table C.1). Similarly, the CICES also has several ecosystem service classes which may support cognitive and mental health benefits (Appendix Table C.1). For example, ecosystem service class 3.1.1.1 includes '*activities promoting enjoyment through active or immersive interactions*', while ecosystem service class 3.1.1.2 includes '*activities promoting enjoyment through passive or observational interactions*'. Both active and passive interactions with nature have been associated with positive benefits for cognition and mental health (Norwood et al., 2019; Pearson and Craig, 2014; Zijlema et al., 2018).

The NESCS uses a different conceptual framework and classification system for determining ecosystem services. Both the supply and demand side are identified to define ecosystem services (US EPA, 2015). Unlike other classification systems, this includes identifying human uses and users of ecosystems (US EPA, 2015). To identify the supply-side, specific ecosystems and their end-products supporting an ecosystem service need to be selected. For example, water extraction for household gardening purposes requires identifying the ecosystem (i.e. rivers and streams) followed by the associated end-product (i.e. liquid water) (see Table 4-1 in US EPA, 2015). To identify the demand-side, the direct use or non-use of the end-product and the user of the end-

product are identified. For example, the direct use of water extraction for household gardening purposes is to support plant or animal cultivation, while the user is the households (see Table 4-1 in US EPA, 2015). Through this approach, the NESCS creates unique ecosystem service categories representing a distinct pathway for linking changes in ecosystems to changes in human welfare (US EPA, 2015).

Problems arise at different stages of the NESCS classification system when determining ecosystem services related to cognitive and mental health. These are described in the following points below in respect to each stage of the NESCS classification:

- *Classification of environment*: When determining an ecosystem service, an environmental class and subclass (i.e. an ecosystem type) needs to be selected (Appendix Table C.2). However, different natural habitat types have been associated with cognition and mental health benefits, making it unclear which environmental class should be selected when determining an ecosystem service related to these health benefits (Akpinar et al., 2016; Maes et al., 2021; Nutsford et al., 2016).
- *Classification of end-products*: An end-product class and subclass need to be selected (Appendix Table C.3). Similar to selecting an environmental class, several end-products may be relevant to cognition and mental health benefits. For example, different groups of flora and fauna have been positively associated with improvements of mental health (Cox et al., 2017b; Taylor et al., 2015), indicating several end-product classes may be relevant to these health benefits. However, end-product class 8 (i.e. composite end-products) does provide an option to define a composite end-product that includes elements and components of a single or multiple environmental classes such as end-product subclasses 81 (i.e. scapes: views, sounds and scents of land, sea sky) or 83 (i.e. presence of environmental class) (Appendix Table C.3). This end-product class may better reflect the fact that multiple end-products within urban ecosystems may be valuable to humans instead of

isolated end-products such as, for example, cognitive and mental health benefits received from exposure to urban ecosystems (US EPA, 2015).

- *Classification of direct use/non-use and direct users*: Determining the direct use class and subclass appears more self-evident with regards to cognitive and mental health benefits. Direct use subclass 12 (i.e. in-situ use) seems accurate for these health benefits (Appendix Table C.4). However, further details within this subclass remain confusing since multiple elements may be relevant to cognitive and mental health benefits such as 1208 (i.e. cultural/spiritual activities) and 1209 (i.e. aesthetic appreciation) (Appendix Table C.4).
- *Classification of direct users*: The selection of the direct user appears more self-evident, where direct user class 2 (i.e. households) is appropriate for determining ecosystem services with regards to cognitive and mental health benefits (Appendix Table C.5).

Reviewing several classification systems for ecosystem services reveals that the classification of cultural services remains unclear, particularly for integrating cognitive and mental health benefits as an ecosystem service. Multiple classifications and their associated descriptions may apply to cognitive and mental health benefits. The structure of the classification of cultural services has been identified as problematic before, and adjustments were made to address these challenges (Haines-Young and Potschin, 2018). The CICES posits that *'it is important to distinguish between what people do or feel in cultural terms from the properties of the ecosystem that enable, facilitate or support those activities or feelings'* (Haines-Young and Potschin, 2018). In other words, the cultural services provided are the characteristics of the urban ecosystem that enable the user to receive cognitive and mental health benefits. Further research is required considering that there are still questions on (i) what characteristics of nature deliver cognitive and mental health benefits, (ii) how to move beyond correlation to causal understanding of these relationships and (iii) what magnitude these characteristics have on cognitive and mental health (Bratman et al., 2019; Franco et al., 2017). Beyond these key

knowledge gaps, the lack of an internationally agreed classification system for ecosystem services also impedes progress to integrate cognitive and mental health benefits as an ecosystem service into urban ecosystem accounts and environmental accounting more broadly. This suggests that considerable progress is needed between experts within the nature, cognition and mental health research and between policymakers on an internationally agreed classification system before cognitive and mental health benefits can be adopted into international environmental accounts according to general accounting principles such as those described in the SEEA EA framework (UN, 2021).

4.4.4. Urban indicators

Indicators are an integral part of accounting to summarise accounting data and statistics to inform decision-making, a process often illustrated through the information pyramid (see Figure 1.1 in Chapter 1). Indicators simplify complex phenomena to provide useful information and can be used to real relative positions or show positive or negative change in a regular interval (UN, 2021). Ongoing efforts have been made to develop environmental indicators within frameworks of sustainability (i.e. the UN SDGs [UN, 2015]), national wealth (Lange et al., 2018) and green growth (OECD, 2017). A wide range of indicators can be derived from the SEEA EA framework for tracking national and global progress but to date are limited in scope, missing a standardised indicator framework that could inform decision-making. The Natural Capital Indicator Framework (NCIF) addresses this problem by *'incorporating the full range of a country's natural assets, the biophysical flows from those assets, the human inputs which may have co-produced these biophysical flows, the benefits deriving from those flows, and the physical residuals from them'* (Fairbrass et al., 2020). The NCIF enables the integration of a large number of relevant indicators into a coherent structure and is intended to be compatible with the SEEA framework and the CICES (Fairbrass et al., 2020; Haines-Young and Potschin, 2018; UN, 2021). To date however, it is not part of these frameworks, nor does it address thematic accounting for urban areas.

The SEEA EA framework provides examples of indicators for ecosystem extent, ecosystem condition and ecosystem service accounts (see Chapter 14 in

UN, 2021). However, there is no reference to potential indicators for physical or monetary ecosystem services flows related to cognition and mental health benefits in the general description of indicators within the SEEA EA framework nor in the thematic accounting for urban areas, but it does not exclude these health benefits either. Nonetheless, the lack of development and integration of biophysical and monetary indicators related to cognition and mental health benefits is a major gap in the health domain of the SEEA EA framework, especially considering the global cost associated with mental ill health and the role of urban ecosystems to contribute to these health benefits (Bloom et al., 2011). The NCIF integrates the health domain into economic indicators of the benefits derived from the environment such as the values associated with avoided health costs (Fairbrass et al., 2020). This may be a way forward to integrate specific health benefits such as cognition and mental health benefits into future urban indicators that inform decision-making and management of urban ecosystems.

4.5. CONCLUSION

My analysis highlights that key gaps remain to account for cognition and mental health benefits received from urban ecosystem exposure into urban ecosystem accounts based on the SEEA EA framework and other associated environmental accounting documents. An analysis of environmental accounting frameworks and associated documents through facilitated discussions as presented in this chapter can be used to better understand how to integrate cognition and mental health benefits as an ecosystem service into thematic accounts for urban areas. Three key points may need to be addressed to move beyond a theoretical approach to standardisation of cognition and mental health benefits across environmental accounting frameworks:

- By addressing knowledge gaps within the nature, cognition and mental health research, published evidence will better address the challenge of integrating cognition and mental health benefits into environmental accounting. This includes, for example, research questions on the mechanisms by which urban ecosystems deliver cognition and mental health benefits to humans and the magnitude of urban ecosystem exposure

compared to other individual-level characteristics such as demographic and socio-economic factors, and contact with nature.

- Better and context-specific data collection of urban areas will be needed to develop and advance thematic accounts for urban areas. This includes, for example, better datasets to (1) classify urban land cover based on the landscape or individual asset approach in a regular interval, and (2) account for other factors such as socio-economic status or visitation rates that are necessary to make meaningful predictions about cognition and mental health benefits in an urban ecosystem account.
- Adapting existing conceptual models for cognition and mental health as an ecosystem service will be needed to integrate these health benefits into thematic accounts for urban areas. This will need to include other factors such as built and human condition indicators of which some, but not all, have already been included to make meaningful interpretations of cognition and mental health benefits received from exposure to urban ecosystems. Part of this challenge requires resolving knowledge gaps as discussed in a previous point, but it will also require standardising the use of other factors in urban ecosystem accounts and environmental accounting more broadly.

This chapter is framed within a broader discussion of the revision of the SEEA framework to include other ecosystem services which are currently not incorporated into standard economic reporting and analyses based on the SEEA CF or the SEEA EA framework. The above-mentioned steps are suggested to address the challenge of integrating cognition and mental health benefits as an ecosystem service into thematic accounts for urban areas. Through these steps, researchers, policymakers and other actors are encouraged to contribute to the integration of these health benefits into environmental accounting frameworks to inform future decision-making and management of urban ecosystems.

CHAPTER 5

Accounting for environmental assets and services has cross-cutting relevance for UK public sector decision-making

This chapter was published in the journal Ecosystem Services and the published paper is provided in Appendix D (Maes et al., 2020).

5.1. ABSTRACT

Countries have made a range of international commitments to compile and use environmental accounts—for example, Sustainable Development Goal (SDG) Targets 15.9 and 17.19, and Aichi Biodiversity Target 2. While processes and methods for compiling environmental accounts are now well defined, mainstreaming environmental accounting across public sector decision-making remains a practical challenge. It raises the question; which domains of public sector decision-making are important in a phased introduction? Here, I addressed a subset of this evidence gap through systematic analysis of the objectives of the entire public sector to understand the policy-relevance of environmental accounts in the United Kingdom (UK). I identified 85 UK public sector bodies whose activities can affect the extent or condition of environmental assets and services, and 60 such bodies whose policy objectives are qualitatively contingent on environmental assets and services. These 60 public sector bodies collectively emphasise environmental management as (1) a key issue for each of these bodies, (2) impacting their public policy objectives by regulating natural hazards, and (3) providing ecosystem goods and services that support health and well-being. My findings highlight the considerable cross-cutting relevance of environmental assets and services to public sector decision-making in the UK, and the need to account for the environment in policy domains beyond those focused narrowly on environmental policy and management

through, for example, coordination structures that feature cross-departmental representation (see Figure 5.1 for graphical abstract).

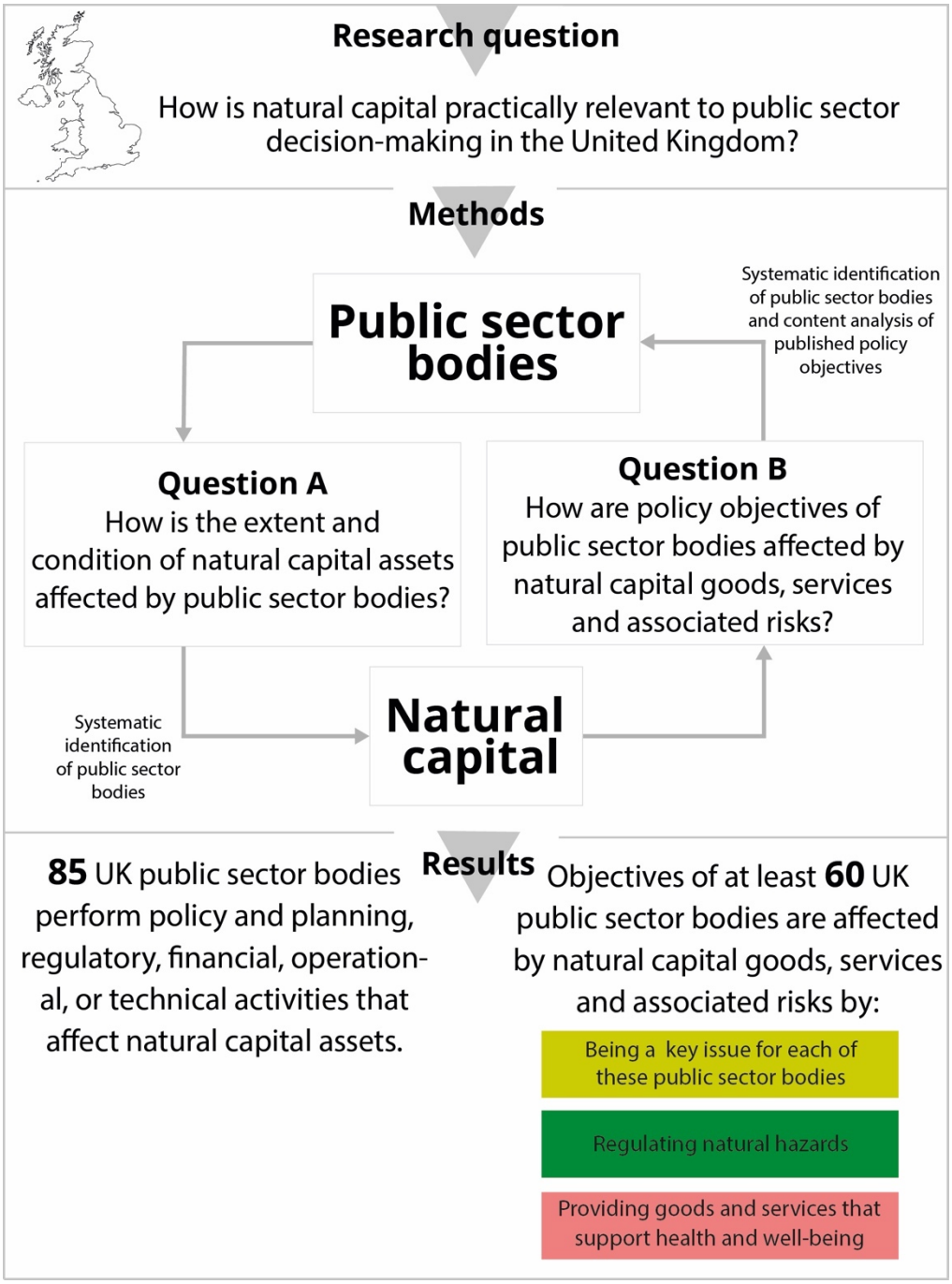


Figure 5.1. Graphical Abstract

5.2. INTRODUCTION

Conventional measures of economic and social development have largely neglected the natural environment, despite its role as the foundation on which our society and economy are built (GLOBE International, 2014; MEA, 2005). The term "natural capital" is increasingly used to describe those parts of the environment that are capable of contributing to human health and well-being, underpinning all other types of capital (i.e. human, financial, manufacturing and social). The proliferation in recent years of environmental data and statistics provide a window of opportunity to organise this information into environmental accounts and associated indicators that enable more holistic analysis of wealth and the environmental sustainability of development (see detailed discussion in Chapter 4; Hammond et al., 1995). Since the 1992 Rio Conference on Environment and Development, the relevance and importance of environmental accounting for public decision-making about sustainable development has been progressively recognised in international political commitments (Chapter 8d in UN, 1992). For example, Sustainable Development Goal (SDG) target 15.9 calls on all countries, by 2020, to "integrate ecosystem and biodiversity values into national and local planning, development processes, poverty reduction strategies and accounts" (UN, 2015b). SDG target 17.19 in a similar vein calls on all countries, by 2030, to "build on existing initiatives to develop measurements of progress on sustainable development that complement gross domestic product, and support statistical capacity building in developing countries" (UN, 2015b).

At a technical level, these commitments are now supported by the UN System for Environmental-Economic Accounting (SEEA) (UN, 2014a). The SEEA is a statistical framework that addresses the need to better account for environmental resources in economic and social accounting, containing a set of standardised concepts, definitions and accounting rules that link environmental data and statistics to economic statistics (see detailed discussion in Chapter 4; UN, 2014a). A global assessment on environmental-economic accounting in 2017 indicated that 69 countries developed programmes already, while 22 countries

were planning a programme on environmental-economic accounting (UN, 2018). Although the adoption of the SEEA was a significant achievement in the evolution of international accounting standards, it did not automatically result in its direct application across policy domains, and a phased introduction to accounting of the environment might be better for political and practical reasons (Vardon et al. 2016). This raises the question; which domains of public sector decision-making are important in a phased introduction?

Integration of environmental policies has been widely debated, even though evidence of actual application is rather inadequate (Jordan and Lenschow, 2010; Lafferty and Hovden, 2003). In particular, mainstreaming environmental accounting across governance and other public sector decision-making bodies remains an important practical challenge for decision-makers. Here, I addressed a subset of this challenge to investigate which domains of public sector decision-making are relevant to environmental accounting. I used the United Kingdom (UK) as our country case study because of national commitments as well as annual environmental and ecosystem accounts it has made in the past and gave a description of the UK's context to environmental accounting in section 2. Through qualitative and consultative methods, I assessed how the status (extent and condition) of environmental assets and services was affected by decision-making across different public sector bodies by reviewing the functions of existing public sector bodies in the United Kingdom. I also examined how accounting and assessment of the environment could support policy objectives of public sector bodies by identifying cross-cutting themes through a consensus-based content analysis of published policy objectives.

5.3. UK CONTEXT

The UK makes a good case study for understanding how to mainstream environmental accounting of assets and services across governance and other public sector decision-making bodies as it has made several national commitments aimed at highlighting the importance of UK's natural assets and make progress on accounting for the environment. The current Government's 2019 manifesto pledged to '*protect and restore our natural environment'* (Conservative Party,

2019). More concrete commitments were made in the UK's Government's 25 Year Environment Plan where it posits to *'improve and expand the range of tools and guidance that support biodiversity net gain approaches, including through the future incorporation of natural capital measures'* or to *'better incorporate the full spectrum of natural capital and the value of the benefits it provides into analysis and appraisal across government'* (Defra, 2018). Since 2013, annual environmental and ecosystem accounts informed by SEEA Central Framework (SEEA-CF) and SEEA Experimental Ecosystem Accounting (SEEA-EEA) have been developed and published by the Office for National Statistics (ONS) and Defra (ONS, 2018; UN, 2014a, 2014b) in partnership with the Natural Capital Committee (NCC). The NCC was initially established in 2012 to advise the UK Government on management of natural capital (NCC, 2017a) and is developing annual reports on the state of the UK's natural capital (NCC, 2019, 2017b). Lastly, the new Green Book, published by Her Majesty's (HM) Treasury in 2018, includes a guidance on the use of non-market values of natural capital in appraisal and evaluation (HM Treasury, 2018).

5.4. METHODS

I assessed UK public sector operating inside and outside the environmental domain for interlinkages with environmental assets, services and associated risks by asking two main questions: How is the status (extent and condition) of environmental assets affected by public sector bodies (Figure 5.2, Question A)? How are policy objectives of public sector bodies affected by environmental assets, services and associated risks (Figure 5.2, Question B)?

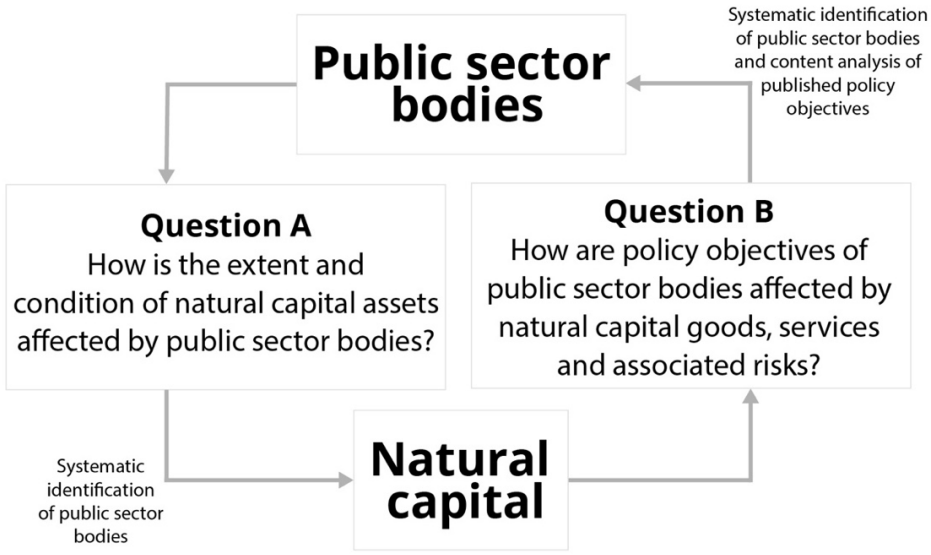


Figure 5.2. Assessing interlinkages between public sector decision-making and delivery bodies, and natural capital.

5.4.1. Public sector bodies that affect the condition of environmental assets

To understand how the status (extent and condition) of environmental assets is affected by the objectives of UK public sector decision-making and delivery bodies (hereinafter referred to as public sector bodies) (Figure 5.2, Question A), I reviewed the data directory of public bodies 2015 (Cabinet Office, 2015) and the UK Government website and other direct web links from this site (HM Government, 2018). I further refined the identification of UK public sector bodies through facilitated discussions between the four authors of the published paper based on this chapter and public servants from Defra who I collaborated with extensively during this analysis, spanning a diverse range of disciplines from environmental sciences, economics, medicine, natural sciences, public policy and law. The inclusion of public servants from Defra was important to have a governmental perspective on the analysis in this chapter and this was further enhanced by a part-time academic secondment to Defra between January and July 2018. The experts did not exclude the possibility that other unidentified public sector bodies might have an association with environmental assets and emphasised that this method does not explain a causal relationship between environmental assets and the objectives of UK public

sector decision-making. The identified public sector bodies were analysed through its geographical jurisdiction and remit:

- What geographical jurisdiction does each identified public sector body act in? The following geographical jurisdictions were considered: UK, England, Scotland, Wales, Northern Ireland and local jurisdictions.
- What function does each identified public sector body exercise? All public sector bodies exercised a functional subset of activities. My typology of functions was based on a consultation with experts, collaboration with public servants and was generally consistent with a policy mapping done by the Crown Estate (Milligan, 2014). It was not based on a review of particular legal frameworks. The following functional activities were considered: policy and planning, regulatory, financial, operational, and technical and advisory function (Table 5.1). I identified only those functions within a public sector body which were explicitly deductible during review of publicly available information on this public sector body. Every public sector body was considered to potentially exercise multiple functions as functions sometimes overlap. The experts did not exclude the possibility that functions of a public sector body might change over time (MacCarthaigh and Roness, 2012).

Table 5.1. Description of the different functions that public sector bodies exercise.

Function	Description	Example
Policy and planning function	The public sector body thinks about and organises activities required to achieve a particular objective, involving the creation and maintenance of a plan.	The Planning Inspectorate deals with planning appeals, planning applications and other planning-related work for various types of infrastructure.
Regulatory function	The public sector body monitors, guides and controls particular public and/or private actors, which can include enforcing government controls and restricting a particular sector.	The Civil Aviation Authority regulates UK airline and airport safety standards, and security arrangements at UK airports.
Financial function	The public sector body manages money in such a manner to support and accomplish the objectives of other public sector bodies.	HM Treasury controls funding of UK farmers and rural communities by allocating financial resources to Defra, the Scottish Government, the Welsh Government and the

		Northern Ireland administration.
Operational function	The public sector body brings together material and/or immaterial assets to produce a particular product or service.	Network Rail operates and develops Britain's railway, which includes tracks, bridges, crossings and stations to deliver well-functioning railway infrastructure to all its users.
Technical and advisory function	The public sector body provides a technical and/or advisory role, which can include the responsibility to manage and share data and statistics.	The UK Expert Committee on Pesticides provides technical advice to the government on the science relating to pesticides.

5.4.2. Policy objectives that are affected by environmental assets

I assessed UK public sector bodies inside and outside the environmental domain and associated policy objectives for interlinkages with environmental assets, services and associated risks. I reviewed institutional objectives using the same list of public sector bodies gathered in section 3.1 (Cabinet Office, 2015; HM Government, 2018) through the following question: Can this public sector body be affected by environmental assets (Figure 5.2, Question B)? I used the Common International Classification of Ecosystem Services (CICES) as a general reference typology for these environmental benefits and risks (Haines-Young and Potschin, 2018). CICES was developed by the European Environment Agency to standardise the way in which ecosystem services are described if international environmental accounting methods were to be further developed and is shaped in part by discussions with the United Nations Statistical Division (Haines-Young and Potschin, 2018).

Following the identification of public sector bodies that can be affected by environmental assets, I developed a description of objectives of each identified UK public sector body. For example, Defra is the 'UK department responsible for safeguarding the natural environment. Defra carries final responsibility for managing the natural environment in England and the UK, including agricultural practices, flood protection and other natural hazards. Therefore, Defra can impact and is impacted by natural capital.' Following the identification of each body's objectives, I then distilled, into a core set of principles, the objectives of all identified UK public sector bodies to identify cross-cutting themes through a consensus-based qualitative content analysis.

This process contained three stages: (1) a short summary consisting of two or three sentences was made for each identified public sector body on how it can be affected by environmental assets, (2) the summaries of stage one were summarised into a maximum set of three themes which can be either a word or a short sentence and (3) a final set of three key themes were identified for all public sector bodies together based on the themes of stage two. For example, in a first stage, Defra is described as 'impacted by natural capital because natural capital drives agricultural productivity in the UK, while its cost-effectiveness is impacted by the natural environment. Simultaneously, natural hazards can disrupt Defra's business of managing the natural environment and agriculture in the country.' In a second stage, Defra's objectives are impacted by natural capital through agricultural productivity, natural hazard disruption and the natural environment being a key objective of Defra itself. In a third stage, I then identified three key themes for all public sector bodies, which is discussed in detail in section 5.5.2. This analysis was informed by Elo and Kyngäs (2008) and enables us to iteratively summarise how UK public sector bodies can be affected by environmental assets in a transparent and reproducible way (Harwood and Garry, 2003). This systematic procedure avoids imposing our own value judgement and minimises subjectivity in the analysis of the normative content. I refined these results through facilitated discussions between the two main authors of this paper until a consensus was reached. Full details on the description of each public sector body's objectives and the qualitative content analysis can be found in Appendix Table D.1 and Table D.2.

5.5. RESULTS

5.5.1. Public sector bodies that affect the condition of environmental assets

I identified 85 public sector bodies out of 315 public sector bodies that perform activities affecting the extent and condition of environmental assets located in the UK (summarised in Figure 5.3 and Appendix Table D.1 and Table D.2). This includes organisations active in a variety of fields such as protecting the environment (e.g. Defra and the Environment Agency), maintaining

and expanding rail and road infrastructure (e.g. Department for Transport (DfT), Network Rail and Highways England) and providing housing (Ministry of Housing, Communities and Local Government (MHCLG) and Homes England). The 85 public sector bodies that were identified are spread across all geographical jurisdictions and 44 out of 85 public sector bodies (52%) were identified to perform uniquely one function. Forestry England, for example, is solely identified to have an operational function by being the largest land manager of public forests in England.

Policy and planning function

United Kingdom
- Department for Business, energy and Industrial Strategy (BEIS)
- Department for Digital, Culture, Media & Sport (DCMS)
- Department for Education (DfE)
- Department for Environment, Food and Rural Affairs (Defra)
- Department for Transport (DfT)
- Department of Health and Social Care (DHSC)
- HM Treasury
- Ministry of Defence (MoD)
- Ministry of Housing, Communities and Local Government (MHCLG)

England
- Environment Agency
- Homes England
- Marine Management Organisation
- Planning Inspectorate

Scotland
- Agriculture and Rural Economy Directorate
- Economic Development Directorate
- Housing and Social Justice Directorate
- Energy and Climate Change Directorate
- Environment and Forest Directorate
- Health Finance Directorate
- Learning Directorate
- Marine Scotland Directorate

Wales
- Economy, Skills and Natural Resources Group
- Education and Public Services Group
- Health and Social Services Group
- Planning Inspectorate

Northern Ireland
- Department for Infrastructure
- Department of Agriculture, Environment and Rural Affairs, incl. Northern Ireland Environment Agency
- Department of Communities
- Department for the Economy
- Department of Education
- Department of Health

Local
- Local authorities

Regulatory function

United Kingdom
- Civil Aviation Authority
- Department for Business, energy and Industrial Strategy (BEIS)
- Department for Digital, Culture, Media & Sport (DCMS)
- Department for Education (DfE)
- Department for Environment, Food and Rural Affairs (Defra)
- Department for Transport (DfT)
- Department of Health and Social Care (DHSC)
- HM Treasury
- Ministry of Defence (MoD)
- Ministry of Housing, Communities and Local Government (MHCLG)
- Office of Gas and Electricity Markets
- Office of Rail and Road (ORR)
- Oil and Gas Authority (OGA)

England
- Environment Agency
- Marine Management Organisation
- The Water Services Regulation Authority

Scotland
- Agriculture and Rural Economy Directorate
- Economic Development Directorate
- Housing and Social Justice Directorate
- Energy and Climate Change Directorate
- Environment and Forest Directorate
- Financial Strategy Directorate
- Health Finance Directorate
- Learning Directorate
- Marine Scotland Directorate

Wales
- Economy, Skills and Natural Resources Group
- Education and Public Services Group
- Health and Social Services Group
- Natural Resources Wales
- The Water Services Regulation Authority

Northern Ireland
- Department for Infrastructure
- Department of Agriculture, Environment and Rural Affairs, incl. Northern Ireland Environment Agency
- Department of Communities
- Department for the Economy
- Department of Education
- Department of Finance
- Department of Health

Local
- Local authorities

Financial function

United Kingdom
- Department for Business, energy and Industrial Strategy (BEIS)
- Department for Digital, Culture, Media & Sport (DCMS)
- Department for Education (DfE)
- Department for Environment, Food and Rural Affairs (Defra)
- Department for Transport (DfT)
- Department of Health and Social Care (DHSC)
- HM Treasury
- Ministry of Defence (MoD)
- Ministry of Housing, Communities and Local Government (MHCLG)

England
- Environment Agency
- Marine Management Organisation
- Rural Payments Agency

Scotland
- Agriculture and Rural Economy Directorate
- Economic Development Directorate
- Housing and Social Justice Directorate
- Energy and Climate Change Directorate
- Environment and Forest Directorate
- Financial Strategy Directorate
- Health Finance Directorate
- Learning Directorate
- Marine Scotland Directorate

Wales
- Economy, Skills and Natural Resources Group
- Education and Public Services Group
- Health and Social Services Group
- The Water Services Regulation Authority

Northern Ireland
- Department for Infrastructure
- Department of Agriculture, Environment and Rural Affairs, incl. Northern Ireland Environment Agency
- Department of Communities
- Department for the Economy
- Department of Education
- Department of Finance
- Department of Health

Local
- Local authorities

Operational function

United Kingdom
- Heritage Lottery Fund
- Ministry of Defence (MoD)
- The Crown Estate
- The Oil and Pipelines Agency
- UK Financial Investments Ltd
- UK Government Investments

England
- East West Railway Company
- English Heritage / Historic England
- Environment Agency
- Forestry England
- High Speed Two (HS2) Limited
- Highways England
- Homes England
- LocatED
- London and Continental Railways Limited (LCR)
- National Forest Company
- Network Rail
- Planning Inspectorate

Scotland
- Forest Enterprise Scotland
- Network Rail
- Scottish Futures Trust
- Transport Scotland

Wales
- Economy, Skills and Natural Resources Group
- Natural Resources Wales
- Planning Inspectorate

Northern Ireland
- Department of Agriculture, Environment and Rural Affairs, incl. Northern Ireland Environment Agency
- Northern Ireland Transport Holding Company (Translink), incl. Ulsterbus, Metro and Northern Ireland Railways

Local
- Local authorities
- Crossrail Ltd
- Ebbsfleet Development Corporation
- National Parks UK
- The Royal Parks
- Transport for London (TfL)

Technical and advisory function

United Kingdom
- Agriculture and Horticulture Development Board
- Civil Aviation Authority
- Industrial Development Advisory Board (IDAB)
- Joint Nature Conservation Committee
- National Infrastructure Commission
- Office of Gas and Electricity Markets
- Office of Rail and Road (ORR)
- Oil and Gas Authority (OGA)
- Regulatory Policy Committee
- Sea Fish Industry
- The Committee on Climate Change
- UK Government Investments
- Universities

England
- Building Regulations Advisory Committee (BRAC)
- Drinking Water Inspectorate
- Forest Commission England
- Natural Capital Committee
- Natural England
- Planning Inspectorate

Scotland
- Convention of Scottish Local Authorities (COSLA)
- Forestry Commission Scotland
- Local Government and Communities Committee
- Scottish Natural Heritage (SNH)
- Transport Scotland

Wales
- Building Regulations Advisory Committee for Wales (BRACW)
- Drinking Water Inspectorate
- Natural Resources Wales
- Planning Inspectorate

Northern Ireland
- Department of Finance
- Northern Ireland Building Regulations Advisory Committee
- Northern Ireland Local Government Association (NILGA)

Local
- Transport for London (TfL)

Figure 5.3. (previous page) Overview of UK public sector decision-making and delivery bodies that perform activities affecting the status (extent and condition) of environmental assets.

National Parks UK consists of 15 National Park Authorities (managed locally): Brecon Beacons Broads, Cairngorms, Dartmoor, Exmoor, Lake District, Lock Lomond & The Trossachs, New Forest, Northumberland, North York Moors, Peak District, Pembrokeshire Coast, Snowdonia, South Downs and Yorkshire Dale. The Royal Parks consists of 10 parks: Brompton Cemetery, Bushy Park, Greenwich Park, Hyde Park, Kensington Gardens, Richmond Park, St James's Park, The Green Park, The Regent's Park and Primrose Hill, and Victoria Tower Gardens. Local authorities were grouped together for the purpose of this analysis into one public sector decision-making body. Raw data of the analysis for each public sector body can be found in Appendix Table D.1 and Table D.2.

5.5.2. Policy objectives that are affected by environmental assets

I identified that the policy objectives of at least 60 public sector bodies are affected by environmental assets in the UK (Figure 5.4A and B, and Appendix Table D.1 and Table D.2). The qualitative content analysis summarises the diverse range of ways by which environmental assets can affect these policy objectives, i.e. environmental management is (1) a key issue for each of these public sector bodies, (2) impacting institutional objectives by regulating natural hazards (e.g. flooding, air quality, climate change), and (3) providing goods and services that support health and well-being (e.g. space for recreation) (Figure 5.4C, and Appendix Table D.1 and Table D.2). Regulation of natural hazards was the most prevalent cross-cutting environmental benefit, being relevant to the policy objectives of 46 out of 60 (76%) identified public sector bodies. Almost half of identified public sector bodies, i.e. 29 out of 60 (48%), are connected to the cross-cutting theme of 'environmental management as a core objective of the organisation', while 24 out of 60 (40%) relevant public sector bodies were classified as affected by environmental assets and services that support health and well-being.

(A) Total of 60 institutions whose objectives are affected by natural capital

United Kingdom
- Agriculture and Horticulture Development Board (AHDB)
- Department for Business, energy and Industrial Strategy (BEIS)
- Department for Digital, Culture, Media & Sport (DCMS)
- Department for Environment, Food and Rural Affairs (Defra)
- Department for Transport (DfT)
- Department of Health and Social Care (DHSC)
- Joint Nature Conservation Committee (JNCC)
- Ministry of Housing, Communities and Local Government (MHCLG)
- Office of Gas and Electricity Markets (Ofgem)
- Office of Rail and Road (ORR)
- The Crown Estate
- United Kingdom Hydrographic Office (UKHO)

England
- Building Regulations Advisory Committee (BRAC)
- Drinking Water Inspectorate (DWI)
- East West Railway Company
- Environment Agency
- Forest Commission England
- Forestry England
- High Speed Two (HS2) Limited
- London and Continental Railways (LCR) Limited
- Marine Management Organisation
- National Forest Company
- Natural England
- Network Rail
- NHS England
- Public Health England
- Rural Payments Agency
- Sports England
- The Water Services Regulation Authority (Ofwat)

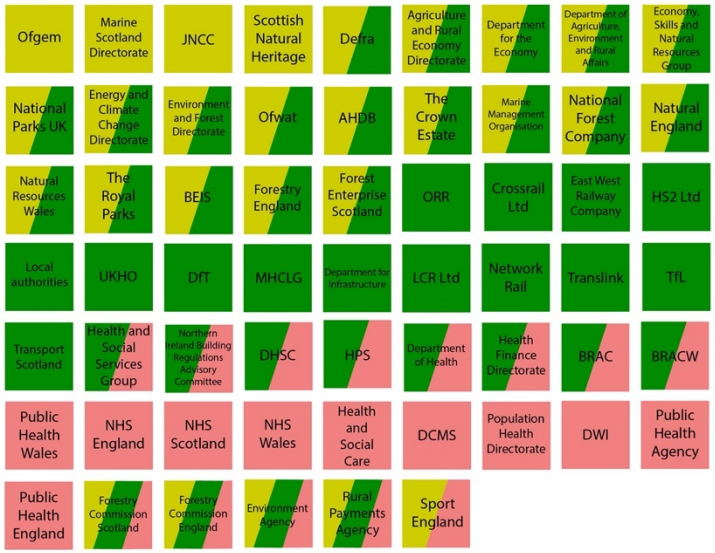
Scotland
- Agriculture and Rural Economy Directorate
- Energy and Climate Change Directorate
- Environment and Forest Directorate
- Forest Commission Scotland
- Forest Enterprise Scotland
- Health Finance Directorate
- Health Protection Scotland (HPS)
- Marine Scotland Directorate
- Network Rail
- NHS Scotland, incl. NHS Health Scotland
- Population Health Directorate
- Scottish Natural Heritage (SNH)
- Transport Scotland

Wales
- Building Regulations Advisory Committee for Wales (BRACW)
- Drinking Water Inspectorate (DWI)
- Economy, Skills and Natural Resources Group
- Health and Social Services Group
- Natural Resources Wales
- Network Rail
- NHS Wales
- Public Health Wales
- The Water Services Regulation Authority (Ofwat)

Northern Ireland
- Department for Infrastructure
- Department of Agriculture, Environment and Rural Affairs, incl. Northern Ireland Environment Agency
- Department for the Economy
- Department of Health
- Health and Social Care
- Northern Ireland Building Regulations Advisory Committee
- Northern Ireland Transport Holding Company / Translink
- Public Health Agency

Local
- Local authorities
- Crossrail Ltd
- National Parks UK
- The Royal Parks
- Transport for London (TfL)

(B) Effects of natural capital on each of the 60 institutions whose objectives are affected by natural capital



(C) Key cross-cutting effects of natural capital on policy objectives

Natural capital is a key issue for each of these public sector bodies

Natural capital regulates natural hazards

Natural capital provides goods and services that support health and well-being

Figure 5.4. (previous page) Summary of the cross-cutting effects of environmental assets on policy objectives.

Different panels show the results of the qualitative content analysis I undertook on (A) identified public sector decision-making and delivery bodies affected by environmental assets, services and associated risks, (B) effects of environmental assets on each of the identified public sector bodies and (C) cross-cutting thematic classification of environmental effects on delivery of institutional policy objectives. Results from (C) are derived from (B), while results from (B) are derived from (A) in a stepwise qualitative content analysis described in more detail in section 5.4.2. See Figure 5.3 for the definition of National Parks UK and The Royal Parks. Local authorities were grouped together for the purpose of this analysis into one public sector decision-making body. Raw data of the analysis for each public sector body can be found in Appendix Table D.1 and Table D.2.

5.6. POLICY IMPLICATIONS

My findings revealed that the objectives of a large number of UK public sector bodies affect or are affected by environmental assets. These public sector bodies cover many policy domains such as transport, energy, health, economy, education, housing, defence, agriculture and environment. This indicates that effects on and from the environment cut across many policies and public sector bodies (GLOBE International 2014), a key feature emphasising that to meet environmental objectives requires integration into non-environmental public sector bodies (Lafferty and Hovden, 2003). The UN SDGs also reflect this cross-cutting relevance because the thematic areas covered by the SDGs are well connected with each other (Le Blanc, 2015; Maes et al., 2019; Scharlemann et al., 2016). This cross-cutting relevance indicates that environmental protection and management could be enhanced by bringing government stakeholders together into coordination structures and processes with broad cross-departmental representation, which has been identified in many domains and sectors before (Keast and Brown, 2010; Klinsrisuk et al., 2013; Korhonen-Kurki et al., 2015; Ruijs et al., 2018).

Even though responsibility for natural capital is often spread across many government departments and other public sector bodies, public pressure and final responsibility is often directed towards respective government departments for environment or other environmental organisations. In 2016, for example, the charity ClientEarth sued and won an air pollution case in High Court against the UK government and particularly the Secretary of State for Environment, Food and Rural Affairs (ClientEarth v Secretary of State for the Environment

Food and Rural Affairs, 2016). Final responsibility for drafting and publishing air pollutions plans comes from Defra, even when regulation of particular air pollution sources might not fall under the responsibility of Defra. During my secondment at Defra, I also did a systematic review of all policy papers published by the UK Department of Health and Social Care (DHSC) between January 2015 and May 2018 (see detailed results in Defra report, Appendix D). In this systematic review, I identified that 5 out of 126 (~4%) policy papers can affect environmental assets, while 13 out of 126 (~10%) policy paper can be affected by environmental assets, suggesting that DHSC is to large extent affected by environmental assets without exerting much management responsibility over these assets (see detailed results in Defra report, Appendix D). This suggests that environmental departments alone (such as Defra) cannot guarantee cross-government action and government departments need to have their own sustainable development strategy without feeling as if it were imposed on them (WWF, 2015). Considering the role cross-departmental structures and processes could play for more effective environmental policy and management, identifying key areas for cooperation and capacity-building should be considered a priority for public sector decision-making.

Successful or effective cross-government coordination related to natural capital depends on well-structured information. A key aspect of compiling national environmental accounts focused on understanding the state of natural capital. Progress has been made by ONS and Defra, in partnership with the NCC, to develop annual environmental and ecosystem accounts (NCC, 2019, 2017b; ONS, 2018, 2017). However, previous research has highlighted the limited knowledge amongst policy decision-makers of natural capital accounting, or how it might be used to support their decision-making (Vardon et al., 2016). Simply accounting for the state of natural capital has not led to the desired adoption by decision-makers for informing policy domains (Vardon et al., 2016). A next step will be to establish strong connections between accounting efforts and strategic cross-governmental natural capital policies. A phased implementation of environmental accounts as suggested by Vardon et al. (2016)

by identifying priority natural capital assets in a country can move accounting of natural capital towards broader adoption in decision-making.

The expenditure of each public sector body is an important component of its impact (or lack thereof) on natural capital. For example, UK environmental accounts estimated that £14.4 billion was spent on environmental protection in 2018 alone, accounting for 1.8% of UK government expenditure (ONS 2018). A majority of the environmental protection expenditure (77.8%) was spent on waste management followed by smaller expenditures such as waste water management, protection of ambient air and climate, and other abatement costs (ONS 2018). Environmental protection expenditure does not give any indication however of direct spend on natural capital. Much of the expenditure goes to goods and services that protect the environment indirectly such as waste processing and recycling, while other expenditures are more evidently related to natural capital such as tree planting schemes and green space creation. UK Government expenditure on natural capital is not yet comprehensively accounted for across Ministerial Departments and other public sector bodies. In particular, data on direct spending to improve natural capital is not consistently gathered across all departments and sectors (Defra 2018). It is unknown if current expenditure is enough to maintain a healthy environment, nor if the expenditure has been well directed and effectively used (Vardon et al., 2016), suggesting the need to comprehensively account for public spending on natural capital.

5.7. CONCLUSIONS AND FUTURE RESEARCH

My findings highlight (1) the considerable cross-cutting relevance of environmental assets to UK public sector decision-making, and (2) the need to account for environmental benefits and impacts in policy domains and institutions beyond those focused specifically on environmental policy and management. A systematic review of public sector bodies through facilitated discussions and qualitative content analyses as presented in this chapter could be used to better understand how to mainstream environmental accounting to non-environmental objectives across public sector decision-making in other

countries. Three key points may be of particular interest to public sector decision-making in the UK and other countries:

- First, public administration and delivery of Government commitments concerning environmental accounting could be enhanced by bringing government stakeholders together through coordination structures and processes that feature broad cross-departmental representation. As I highlighted, many policy domains and public sector bodies beyond those that traditionally focus on environmental policy and management can affect or can be affected by environmental assets. Identifying, across public sector bodies, specific priority areas for cooperation and capacity-building concerning environmental assets will be necessary for effective protection and enhancement of the environment.
- Second, connecting environmental accounting with strategic environmental objectives and policies can help identify, for example, priority environmental assets in a country and deliver a step-by-step and cost-effective agenda towards improving the state of the environment. It can also help identify best practices and methods for win-win scenarios for policy delivery and natural capital management.
- Third, comprehensively accounting for public spending on environmental assets could help clarify the role of different policy domains and public sector bodies to environmental policy and management. As indicated by others, it could also help identify if public spending is enough to maintain a healthy environment, or if spending is well directed or effectively used (Vardon et al., 2016).

CHAPTER 6

Discussion and conclusion

6.1. RESEARCH OVERVIEW

In this thesis, I tackled one main aim: to explore existing scientific knowledge gaps between human health and urban ecosystem exposure, the barriers to integrate this information into urban ecosystem accounting, and use of these outputs in public policy to inform decision-making and support sustainable development of urban ecosystems. To achieve this aim, I first demonstrated the interrelationships between urban ecosystem management and other sustainable development goals, highlighting the challenge of cross-disciplinary cooperation to resolve existing knowledge gaps. I went on to address a subset of this challenge by improving our understanding of the association between adolescent's cognitive development and mental health, and exposure to urban ecosystems. Next, I reviewed international environmental accounting frameworks to understand how to integrate urban ecosystem data and statistics related to cognitive development and mental health benefits into these frameworks. Finally, I investigated how to improve the adoption of urban ecosystem science and accounting by public sector decision-making. The academic fields of environmental epidemiology, environmental accounting and environmental policy are usually studied separately but here I join these together to assess how to connect science with policy for sustainable development of urban ecosystems.

6.2. SUMMARY OF KEY FINDINGS

To assess the interrelationships between management of urban ecosystems and other development goals, I analysed the content of the UN SDG targets to identify those SDG targets that stipulate action in relation to urban ecosystems using a consensus-based qualitative content analysis. I also identified evidence of empirical relationships (synergies or trade-offs) between action to deliver a SDG target and actions to invest in, conserve and enhance urban ecosystems

through a extensive literature review consisting of published studies in peer-reviewed journals and reports published by non-academic organisations. I showed that, as expected, various UN SDGs are linked to urban ecosystem management. Addressing academic siloed-thinking and making interdisciplinary work standard practise will better address the challenge of interlinkages between themes affecting urban ecosystems and suggests that access and integration of published evidence generated from interdisciplinary research is important to support policies and decision-making. One way to do this, for example, is by including the value of urban ecosystems into urban accounts and indicators. However, many benefits provided by urban ecosystems are currently not well understood, and we need more interdisciplinary research for assessing the health and well-being benefits received from urban ecosystems.

Unfortunately, assessing the health and well-being benefits received from urban ecosystem is difficult, particularly for adolescent's cognition and mental health benefits received from exposure to urban ecosystem which is relatively understudied (Bijnens et al., 2020; Dadvand et al., 2015a; Engemann et al., 2019). The field of nature, cognition and mental health research has established associations between urban nature, cognitive development and mental health, but what type of urban ecosystems most influence these patterns remain unclear. I characterised London's urban ecosystems by analysing the types of natural environment using remote-sensing data, LiDAR data and other data sources. I also used longitudinal data in a cohort of 3,568 adolescents aged 9 to 15 years at 31 schools across London to develop a model and examine the associations between natural environment types, including green and blue space, and adolescent's cognitive development, mental health and overall well-being. I showed that, after adjusting for other environmental, demographic and socioeconomic variables, exposure to natural environments and particularly woodland was associated with enhanced cognitive development and mental health during adolescence. This suggests that optimising ecosystem services linked to cognitive development and mental health benefits should prioritise the type of natural environment.

Despite the progress made to understand cognitive development and mental health benefits received from exposure to urban ecosystems, translating urban ecosystem data and statistics related to these health benefits into standardised environmental accounts and indicators remains a practical challenge. The UN SEEA-EA framework and a variety of related international and national policy documents have expanded on the use of environmental accounting for developing urban ecosystem accounts, but to date it remains unclear how to standardise cognitive development and mental health benefits as ecosystem services in these accounts. I reviewed the thematic assessment for urban areas from the SEEA EA framework to assess its suitability for integrating cognitive and mental health benefits as an ecosystem service. Unfortunately, I found that considerable progress is needed at all stages of developing urban ecosystem accounts (i.e. when assessing ecosystem extent, ecosystem condition and ecosystem service) before cognitive development and mental health benefits can be adopted into international environmental accounts such as the SEEA EA framework. This included, for example, practical challenges with ecosystem type and ecosystem service classification systems, and knowledge gaps with regards to the nature and mental health conceptual framework. Resolving these challenges is important to inform decision-making processes for urban ecosystems, and sustainably develop urban ecosystems.

In addition to the challenges to develop urban ecosystem accounts and statistics related to cognitive development and mental health, the application of these urban ecosystem accounts and statistics into decision-making processes is not necessarily guaranteed. In particular, how to mainstream environmental accounting across public sector decision-making, including urban ecosystem science and accounting, is poorly known. I investigated how to improve the adoption of urban ecosystem science and accounting by public sector decision-making. To do this, I reviewed all UK public sector bodies operating both inside and outside the environmental domain to assess interlinkages between public sector objectives and natural capital goods, services and associated risks by reviewing the data directory of public bodies 2015 (Cabinet Office, 2015) and the UK Government website and other direct web links from this

site (HM Government, 2018). I found that there is considerable cross-cutting relevance of environmental accounting for UK public sector decision-making and that there is a need to account for environmental benefits and impacts in policy domains and institutions beyond those focused specifically on environmental policy and management. These findings suggest that environmental policy and management could be enhanced by bringing stakeholders together through coordination structures and processes that feature broad cross-departmental representation and would be a necessary step towards sustainably developing urban ecosystems.

6.3. RESEARCH IMPLICATIONS

As I have shown, addressing the issue of sustainable development of urban ecosystems requires taking into account a variety of economic, environmental and social domains (Maes et al., 2019, see Chapter 2). I addressed a subset of this challenge by focusing on the role of urban ecosystems for cognitive development and mental health and how this knowledge may, or may not, effectively inform public policy and decision-making. My research highlighted that there are ways to connect data and statistics on human health with broader decision-making, supporting the concept of a framework that places data and information into the centre of the policy process, also referred to as the policy cycle (EEA, 2011). One way to do so is by including data and statistics on urban ecosystems into urban accounts and indicators, enabling published evidence from interdisciplinary research to inform decision-making.

I present evidence to suggest that efforts to sustainably develop our societies and economies have not prioritised urban ecosystems. Discussions on the integration of scientific data and statistics into environmental accounting have not considered urban ecosystems as a primary focus, despite the scientific evidence that indicates a beneficial role of urban ecosystems for human health and well-being such as the cognitive development and mental health benefits received from urban ecosystem exposure (see detailed discussion in Chapter 3). For example, international environmental accounting such as the SEEA CF and SEEA EEA framework primarily focus on national accounting, where priority is given to large environmental assets and its associated ecosystem

services; in fact, the SEEA EEA framework posits that *'while urban ecosystems may be of interest, often they may not be considered a focus of ecosystem accounting'* (UN, 2014b). However, there is growing interest in the ability of urban ecosystems to deliver benefits to human health and well-being (Maes et al., 2021, see Chapter 3). For example, the newly adopted SEEA EA framework includes a specific environmental theme on developing urban ecosystem accounts for the first time (UN, 2021) (see detailed discussion in Chapter 4), but to date the process of integrating data and statistics on cognitive development and mental health benefits into these accounts is nascent. Further developing this interdisciplinary field of urban ecosystem science, economics and policy integration is important for enabling scientific evidence of urban ecosystems to inform future decision-making. I translate the challenge of this field into three key issues that need to be addressed: (1) evidence gaps, (2) lack of cross-disciplinary cooperation and (3) lack of methodological integration.

6.3.1. Evidence gaps

Each data chapter in this thesis had specific key gaps and I have outlined these in Figure 6.1a. These chapter-specific gaps can be aggregated into three key conclusions to advance the field of urban ecosystem science, economics and policy integration (Figure 6.1b). One of these key conclusions is that key evidence gaps remain in all disciplines studied in this thesis, including evidence gaps within the field of environmental epidemiology, environmental accounting and public policy (see detailed discussion of specific evidence gaps in section 6.5 'Future Research' below). The interlinkages between urban ecosystems and other sustainable development domains make it difficult to address certain evidence gaps (see detailed discussion in Chapter 2) including, for example, the health and well-being benefits received from urban ecosystem exposure as researched in this thesis (see detailed discussion in Chapter 3). This indicates that to address these evidence gaps across multiple academic disciplines, issues of academic silo-thinking need to be addressed by making interdisciplinary work standard practise. Resolving key knowledge gaps also

requires better data collection of urban areas and recognition of this information will better support urban policy and management (Figure 6.1b).

6.3.2. Lack of cross-disciplinary cooperation

Another key conclusion is that cross-disciplinary cooperation will better address the challenges urban ecosystems face to develop sustainably because of the interlinkages with other sustainable development domains (Figure 6.1b) (Maes et al., 2019, see detailed discussion in Chapter 2). This implies the need of bringing stakeholders together through coordination structures and processes that feature broad cross-disciplinary representation. For example, this thesis established cross-disciplinary cooperation by working across different academic departments and universities and within a government department to address the research questions of this thesis (see section 1.2.5 in Chapter 1). This included academic experts spanning the fields of environmental epidemiology, environmental accounting and public policy from the Centre for Biodiversity and Environment Research and Department of Law at University College London, the Department for Biostatistics and Epidemiology at Imperial College London, Yale School of the Environment at Yale University, and the UK Government Department for Environment, Food and Rural Affairs. Despite the advantages of developing this multidisciplinary context to address the research questions of this thesis, it did bring about a variety of unforeseen challenges such as communication and methodological differences which suggest a need for deeper integration (see detailed discussion in section 6.3.3 below).

6.3.3. Lack of methodological integration

Cross-disciplinary cooperation as established in this thesis brought about unforeseen challenges hindering the main aim. Communication differences were common. Experts often used different disciplinary jargon and aligning expert's perceptions and expectations was a practical challenge, especially within the multidisciplinary context of this thesis. However, regular and structured cross-disciplinary communication did help mitigate this issue. In addition, considerable methodological differences between academic disciplines was problematic. Research findings developed following a particular academic discipline

were not easily connectable with the research developed in another academic discipline. For example, results from my epidemiological model (as developed in Chapter 3) directly addressed a scientific question and framework but did not necessarily address policy questions and frameworks, nor was it clear how these model results were relevant for econometric models. Scientists and economists maintain different interpretations of correlation and causation, and use a different disciplinary jargon (as discussed above), complicating the use of scientific results into environmental accounting and use of these accounts into environmental indicators. Although the multidisciplinary context of this thesis allowed me to address the main aim of this thesis, each discipline informed other disciplines while maintaining its own methodology. Further developing this interdisciplinary field of urban ecosystem science, economics and policy integration will require a deeper methodological integration between the disciplines to resolve existing barriers and recognise cognition and mental health benefits into public policy and decision-making. A deeper methodological integration may be achieved in academia, for example, by setting up cross-disciplinary working groups that focus solemnly on the challenge how research findings from different disciplines can inform one another, but to date such working groups are often difficult to establish because of existing academic pressures such as publication pressures.

6.4. LIMITATIONS OF THE CURRENT WORK

A limitation of the research conducted in this Ph.D. thesis is that it was conducted on different spatial scales including global and national policy perspectives, and a city-wide empirical study. However, differences in scale may not be problematic. For example, the correlations of cognition and mental health with urban ecosystem type are likely generalisable to other environments outside of the London metropolitan area since the school population selected in this research was deliberately chosen to be representable for the general school population in the UK (Taylor et al., 2015). Although generalisable to the UK, other countries may be different (Akpinar et al., 2016). In addition, global political commitments for sustainable development (see detailed discussion in Chapter 2) or environmental accounting frameworks such as the SEEA EA

framework (see detailed discussion in Chapter 4) are relevant and influence public policy and decision-making in London, especially considering that the UK Government is a UN member and is an active member in the development of these policy frameworks. From this perspective, the different spatial scales may also be considered a strength of this thesis because I used the London metropolitan area as a case study for urban ecosystems, while framing the challenges these urban ecosystems face within a broader national and global context.

The findings of this thesis highlight the connection of data and statistics on human health and well-being with broader decision-making through urban ecosystem accounts and indicators, but to date the process of integrating specific human health data and statistics on cognitive development and mental health benefits into these accounts is nascent. However, I did not explore how this process can become relevant to end-users of urban ecosystems such as smaller organisations, households or individuals, amongst others. Many end-users of urban ecosystems may affect or may be affected by urban ecosystems and do not necessary use or value urban ecosystem accounts or indicators when making decisions on urban ecosystems. Nonetheless, these end-users may play important roles to sustainably develop and manage urban ecosystems. The role of citizens in science and decision-making has been discussed considerably, and suggestions have been made to further develop the field of civic science which is defined as *'efforts by scientists to reach out to the public, communicate scientific results and contribute to scientific literacy'* (Bäckstrand, 2003). Citizen science is increasingly being used to involve citizens in scientific research (Schröter et al., 2017). However, the role of citizens is often limited to data collection and analyses, while the are excluded from data interpretation and dissemination of results (Schröter et al., 2017). In the US, for example, suggestions were made to involve the community by raising awareness of the health benefits of nature, partnering with outdoor organisations to offer new outdoor experiences or develop entirely new programmes with hospitals or clinics (Himschoot et al., 2020). Similarly, the UK Government announced a 4 million investment to prevent and tackle mental ill health through green social

prescribing, where health care workers will prescribe people with nature-based interventions and activities such as local walking, community gardening or food-growing projects (Defra, 2020). By finding solutions to involve end-users, decisions about how to sustainably develop urban ecosystems may be better informed in the future.

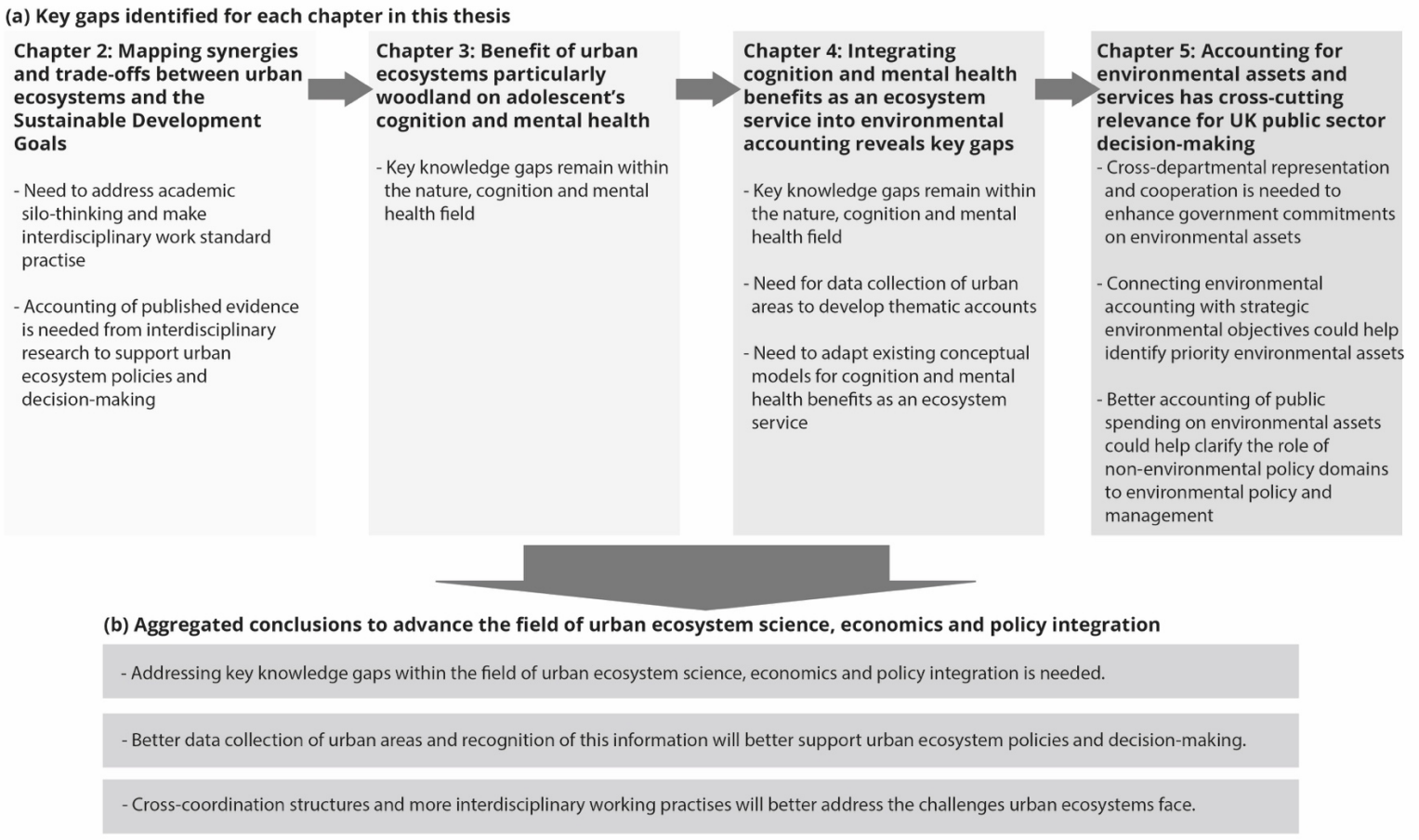


Figure 6.1. Overview of key gaps identified in each data chapter of this thesis (i.e. Chapter 2, 3, 4 and 5) and the key conclusions based on aggregating these key gaps to advance the field of urban ecosystem science, economics and policy integration.

6.5. FUTURE RESEARCH

My research suggests that not every type of natural environment may contribute equally to cognitive development and mental health benefits, and creates potential opportunities for future urban planning decisions. However, my findings also expose key knowledge gaps remaining in the nature, cognition and mental health research (Figure 6.1). In particular, it lacks evidence of a mechanistic understanding why particular natural environments may provide a protective factor for adolescent's cognitive development and mental health, while other natural environments may not (Franco et al., 2017). As discussed in detail in Chapter 3, higher audio-visual exposure to vegetation or animals in woodland have been documented to improve mental health, of which both features are expected in higher abundance in woodland (Hedblom et al., 2014; Irvine et al., 2009). In addition, inhalation or ingestion of phytoncides, negative air ions or microbes may well explain non-sensory physiological pathways through which these health benefits may be received from nature (Li, 2010; Rook et al., 2012). Despite the uncertainties of the mechanisms by which we receive these health benefits, I believe that my research does create interesting opportunities to develop, manage and invest in natural environments and particularly woodland to improve adolescent's cognitive development and mental health, especially in those areas where adolescents spend most time such as their residence and school. Further research will need to be done to replicate these findings.

When taking a broader perspective on the knowledge gaps identified in each chapter of this thesis, these gaps hinder the practical challenge on how to sustainably develop urban ecosystems. One of the conclusions to advance the field of urban ecosystems science, economics and policy integration focused on the need to develop cross-coordination structures and more interdisciplinary working practises (Figure 6.1). This could develop answers for key knowledge gaps. Currently, researchers and decision-makers develop research and action plans related to urban ecosystems on their own but there is no coordinated approach to decide, for example, what measures of cognition and mental health are representable. Although a lot of important and useful research

has been developed, the uncoordinated approach makes it difficult to cross-compare, and therefore the field itself does not advance. More interdisciplinary Ph.D. projects such as mine could enable a new generation of researchers to establish more interdisciplinary working practices. However, there are other examples where people try to align and harmonise research for the purpose of advancing the field and facilitate cross-comparison. For example, the Data Harmonization working group chaired by Greg Farber recommended a common set of data collection measures within mental health science (Farber et al., 2020). However, the opposite has also been advocated where the dangers of standardising mental health measures can lead to magnifying scale-specific issues and reaffirming diagnostic hegemonies, amongst others issues (Patalay and Fried, 2020). Even though the debate on more or less collaboration across disciplines and harmonization of findings is alive and kicking, this thesis does highlight that there is currently a need for more collaboration and harmonization, and future research will need to identify where the fine balance lies.

6.6. CONCLUSIONS

Urban ecosystems provide a range of services to human health and well-being, but currently face monumental challenges because of urban population growth and associated unsustainable management of urban ecosystems. A better understanding of the requirements to sustainably manage urban ecosystems is required to protect, manage and expand urban ecosystems in order to improve human health and well-being in the future. This study highlights key impediments and the potential of cross-disciplinary cooperation as a tool to sustainably develop urban ecosystems, by generating cross-disciplinary coordination structures on all levels of governance relevant to the management of urban ecosystems. If the tools and findings of this study are further developed and researched, this information could be used to inform decisions about how to sustainably develop urban ecosystems in the future. Three key points may be of particular interest to address the challenges of sustainable development of urban ecosystems:

- Key evidence gaps remain in all disciplines studied in this thesis. This included evidence gaps within the field of environmental

epidemiology, environmental accounting and environmental public policy. By addressing academic silo-thinking and making interdisciplinary work standard practice, evidence gaps may be resolved to advance the field of urban ecosystem science, economics and policy integration.

- A lack of cross-disciplinary cooperation not only leads to unresolved knowledge gaps but may also result in unsustainable management of urban ecosystems. More cross-disciplinary cooperation will better address the challenges urban ecosystems face to develop sustainably because of the interlinkages with other sustainable development domains This implies the need of bringing stakeholders together through coordination structures and processes that feature broad cross-disciplinary representation.
- Communication and methodological differences suggest a need for deeper methodological integration of disciplines, including in the field of urban ecosystem science, economics, and policy integration. For example, different interpretation of model results and the use of different disciplinary jargon complicate the use of scientific results into environmental accounting and use of these accounts into environmental indicators. A deeper methodological integration may be achieved, by setting up cross-disciplinary working groups that focus solely on the challenge how research findings from different disciplines can inform one another.

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Table A.1. Overview of each Sustainable Development Goal (SDG) target to assess its relation to urban ecosystems.

(A) SDG targets that stipulate certain actions to urban ecosystems and (B) SDG targets for which there is published evidence of synergies or trade-offs with decisions to invest in, conserve or enhance urban ecosystems. SDG targets with no identified relation to urban ecosystems are excluded from this table.

SDG target	A	B		Reasoning	References
		Synergies	Trade-offs		
Goal 1. End poverty in all its forms everywhere					
1.1		X	X	(B) Evidence of interlinkages between poverty and the environment in cities (e.g. nutrition or drinking water). Eradicating poverty needs to be supported by providing access to ecosystem services for all people.	(Alix-Garcia et al., 2015; Alkire et al., 2014; Angelsen et al., 1998; Duraiappah, 1998; ECOS Magazine, 2008; Richards et al., 2017; Stern et al., 1996)
1.2		X	X	As 1.1.	As 1.1
1.4	X	X	X	(A) Target calls for access to economic resources, which includes natural resources and land property (B) Evidence that access to natural resources and its properties can affect the ability of countries to invest in, conserve and enhance ecosystems in cities	(Scherr, 2000)
1.5	X	X	X	(A) Target calls for changes to the environment in cities to make cities (and the poor living in them) more resilient to climate-related events and environmental shocks (B) Evidence of synergies and trade-offs with the ability to invest in, conserve and enhance ecosystems in cities through e.g. climate adaptation structures.	(Eriksen et al., 2007)

1.a	X	X	X	(A) Target calls for mobilisation of resources to end poverty in all its dimensions, including poverty eradication through investment in ecosystems in cities (B) Mobilising additional resources will affect the ability to invest in, conserve and enhance ecosystems in cities.	Probably link but cannot find any evidence
Goal 2. End hunger, achieve food security and improved nutrition, and promote sustainable agriculture					
2.1	X	X	X	(A) Target calls for changes in food systems, which includes land currently occupied by ecosystems in cities (B) This target has synergies and trade-offs with the ability to invest in, conserve and enhance ecosystems in cities, for instance through small-scale agricultural practices within the city boundaries to increase the sustainability of the city.	(Mougeot, 2000; Newman, 1999; Pearson et al., 2011)
2.3	X	X	X	As 2.1.	As 2.1
2.4	X	X	X	(A) Target calls for sustainable and resilient food production systems and agricultural practises that help maintain ecosystems; urban agriculture is a means for a city to become more self-reliant and produce more local foods, which help strengthen the capacity for for adaptation to climate change (B) Evidence of synergies and trade-offs between this target and the ability to invest in, conserve and enhance ecosystems in cities.	As 2.1
2.5	X	X		(A) Target calls for action to maintain genetic diversity of wild species, including wild species present in urban ecosystems (B) Evidence of	(Frankham et al., 2002)

				synergies between this target and the ability to invest in, conserve and enhance ecosystems in cities.	
2.a		X	X	(B) Evidence that increased investment in agricultural research and enhancing agricultural productive capacity has both synergies and trade-offs with the ability to invest in, conserve and enhance ecosystems in cities.	(Aldy et al., 1998; Allen, 2003; Tilman et al., 2001)
Goal 3. Ensure healthy lives and promote wellbeing for all at all ages					
3.9	X	X		(A) Target calls for the reduction of hazardous chemicals and air, water and soil pollution and contamination, which includes pollution and contamination that could leak into the environment in cities (B) Evidence of synergies that reduction of chemicals and other pollutants affect the ability to invest in, conserve and enhance ecosystems in cities.	(Bobbink et al., 1998; Hartig et al., 2014; Philp et al., 2005)
3.c	X	X		(A) Target stipulates to increase health financing which includes investments into health benefits by managing the environment in cities (B) Evidence of synergies between investment in health and the ability to invest in, conserve and enhance ecosystems in cities.	(Hartig et al., 2014)
3.d	X	X		(A) Target stipulates to strengthen capacity of managing health risks which includes potential changes to the environment to manage health risks (B) Evidence of synergies between the ability to invest in, conserve and enhance ecosystems in cities.	(Foley et al., 2005; Lowe et al., 2011; Patz et al., 2004)
Goal 4. Ensure inclusive and equitable quality education and promote life-long learning opportunities for all					

4.7	X	X	(A) Target inclusive of knowledge and skills related to the environment (B) Evidence that education in sustainable development and lifestyles has synergies with the ability to invest in, conserve and enhance the environment in cities.	(Pimbert and Pretty, 1997)
4.b	X		(A) Target requires action related to the skills and training needed to invest in, conserve and protect the environment in cities.	
Goal 5. Achieve gender equality and empower all women and girls				
5.1		X	(B) Evidence that empowerment of women and ending discrimination of women has synergies with the ability to conserve urban ecosystems.	(MEA, 2005; UNEP, 2016)
5.a		X	(B) As 5.1	As 5.1
5.c		X	(B) As 5.1	As 5.1
Goal 6. Ensure availability and sustainable management of water and sanitation for all				
6.1	X	X	(A) Target calls for equitable access to safe drinking water, which includes water potentially harvested from ecosystems in cities (B) Evidence of synergies and trade-offs between this target and the ability to invest in, conserve and enhance ecosystems in cities	(Gleick, 2000; Owusu et al., 2003; Viala, 2008)

6.2	X	X	X	(A) Target calls for access to sanitation facilities and to end open defecation which can affect the environment in cities (B) Evidence of synergies and trade-offs between this target and the ability to invest in, conserve and enhance ecosystems in cities.	(Chanakya and Sharatchandra, 2008; Mihelcic et al., 2011)
6.3	X	X		(A) Target stipulates changes to the environment in cities by minimising water usage and water pollution (B) Evidence of synergies with the ability to invest in, conserve and enhance ecosystems in cities.	As 6.1 (Turner and Rabalais, 1991)
6.4	X	X		As 6.3.	As 6.3
6.5	X	X		(A) Target calls for integrated water resources management, also related to the environment through e.g. hydropower and river management (B) Evidence that better management of water can affect the ability to invest in, conserve and enhance ecosystems in cities.	(UNEP, 2014)
6.6	X	X		(A) Target calls for restoration of water-related ecosystems, including ecosystems located in cities (B) Evidence of synergies between restoration of water-related ecosystems in the ability to invest in, conserve and enhance ecosystems in cities.	(Ramsar Convention, 2010)

6.a	X	X		(A) Target calls for cooperation and capacity-building in water- and sanitation-related activities which can affect the environment in cities (B) Evidence of synergies between this target and the ability to invest in, conserve and enhance ecosystems in cities.	As 6.3
6.b	X	X		(A) Target calls for strengthening water and sanitation management which can affect the environment in cities (B) Evidence of synergies between this target and the ability to invest in, conserve and enhance ecosystems in cities.	(Carter et al., 1999)
Goal 7. Ensure access to affordable, reliable, sustainable and modern energy for all					
7.1	X		X	(A) Access to modern energy services stipulates potential changes to the environment in cities through land-use changes (B) Evidence of trade-offs between providing modern energy services and the ability to invest in, conserve and enhance ecosystems in cities.	(Al-Riffai et al., 2010; Hernandez et al., 2014; Pataki et al., 2006; Searchinger et al., 2008; Sokka et al., 2016)
7.2	X		X	(A) Increasing renewable energy stipulates potential changes to the environment in cities through land-use changes (B) Evidence of trade-offs between providing more renewable energy and the ability to invest in, conserve and enhance ecosystems in cities.	As 7.1

7.b	X		X	(A) Expanding infrastructure stipulates a change to the environment in cities through land-use changes (B) Evidence of trade-offs between expanding and upgrading energy infrastructure and related technology and the ability to invest in, conserve and enhance ecosystems in cities.	As 7.1
Goal 8. Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all					
8.1	X	X	X	(A) Target requires action related to the environment. By investing in economic growth there can be an impact on the environment. (B) Evidence of synergies and trade-offs between economic growth and the ability to invest in, conserve and protect ecosystems in cities. For example, economic growth traditionally is accompanied with environmental degradation through spatial trade-offs.	(Shafik, 1994)
8.2	X	X	X	(A) Target requires action related to the environment. By investing in economic productivity there can be an impact on the environment. (B) Evidence of synergies and trade-offs between economic productivity and the ability to invest in, conserve and protect ecosystems in cities. For example, an increase in economic productivity traditionally can be accompanied with environmental degradation through spatial trade-offs	As 8.1

8.4	X	X		(A) Target requires action related to the environment, by minimizing the impact of economic growth on the environment and resources (B) Evidence of synergies between this target and the ability to invest in, conserve and enhance ecosystems in cities.	As 8.1
Goal 9. Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation					
9.1	X	X	X	(A) Target calls for changes in infrastructure, including environmental infrastructure (B) Evidence that quality, reliable, sustainable and resilient infrastructure has synergies and trade-offs with the ability to invest in, conserve and enhance ecosystems in cities.	Probably link but cannot find any reference
9.2		X	X	(B) Evidence of interlinkages between industrialisation and environmental degradation, which also impacts the ability to invest in, conserve and enhance ecosystems in cities..	(Muradian et al., 2002)
9.4	X	X	X	(A) Target calls for policies to promote resource efficiency and adoption of environmentally sound technologies, which is related to the environment in cities (B) Evidence that resource efficiency and environmentally sound technologies has an impact on the ability to invest in, conserve and enhance ecosystems in cities.	(Dijkmans, 2000)

9.5	X	X	X	(A) Target stipulates scientific research and technological capabilities that can also be relevant to the environment in cities (B) Evidence of synergies and trade-offs between enhancing scientific research and technological capabilities and the ability to invest in, conserve and enhance ecosystems in cities.	(Shannon et al., 2008)
9.a	X	X	X	(A) Target calls for financial technological and technical support for sustainable and resilient infrastructure, include environmental support (B) Evidence of synergies and trade-offs with the ability to invest in, conserve and enhance ecosystems in cities.	Probably link but cannot find any reference
9.b		X	X	(B) Evidence of interlinkages between supporting technology development, research and innovation for industrial diversification and the environment in cities through e.g. spatial relationships.	As 9.2
Goal 10. Reduce inequality within and among countries					
10.1		X	X	(B) Evidence of synergies and trade-offs between income growth and the ability to invest in, conserve and enhance ecosystems in cities (As 1.1).	As 1.1
10.b	X	X	X	(A) Target inclusive of official development assistance commitments related to the environment in cities (B) Evidence of synergies and trade-offs between encouraging development assistance and the ability to invest in, conserve and enhance ecosystems in cities.	(Hicks et al., 2010)

Goal 11. Make cities and human settlements inclusive, safe, resilient and sustainable					
11.1	X	X	X	(A) Target calls for upgrade of slums and basic services related to the environment. (B) Evidence that upgrading housing can affect the ability to invest in, conserve and protect the environment in cities.	(Gopal and Nagendra, 2014; Pauleit et al., 2005)
11.2	X	X	X	(A) target calls for access to sustainable transport systems and improving road safety, which can entail spatial relationships with the environment in cities (B) Evidence of interlinkages between access to transport systems and the ability to invest in, conserve and enhance ecosystems in cities.	(Button and Rothengatter, 1993)
11.3	X	X	X	(A) Target calls for greater participation in urban planning, which includes decision making on the environment (B) Evidence that greater participation in urban planning has synergies and trade-offs with the ability to invest in, conserve and enhance the environment in cities.	(Rosol, 2010)
11.4	X	X		(A) Target calls to protect and safeguard natural heritage including the environment in cities (B) This target has synergies with the ability to invest in, conserve and enhance ecosystems in cities	(Bengston and Youn, 2006)
11.5	X	X	X	(A) Target calls for reduction of disasters which includes risk reduction measures that can change the environment in cities (B) Reduction of natural disasters in this target can have synergies or trade-offs with the ability to invest in, conserve and enhance ecosystems in cities	(Bao and Chen, 2004)

11.6	X	X	X	(A) Target calls to reduce the per capita environmental impact of cities (B) Synergies between this target and the ability to invest in, conserve and enhance ecosystems in cities	(Douglas et al., 2016; Hartig et al., 2014; Liu et al., 2008; Pearson et al., 2015; Zhao et al., 2011)
11.7	X	X		(A) Target calls to provide green and public spaces which is directly related to the environment in cities (B) As 11.6	(Dunn, 2010; Wolch et al., 2014)
11.a	X	X		(A) Target calls to develop environmental links between urban and rural areas which is directly related to the environment in cities (B) As 11.6	(Ignatieva et al., 2011)
11.b	X	X	X	(A) Target calls for integrated policies and plans related to the environment (B) Evidence that integrated policies and plans towards climate change mitigation and adaptation has synergies and trade-offs with the ability to invest in, conserve and protect the environment in cities.	(Gill et al., 2007; Kleerekoper et al., 2012)
11.c		X		(B) Building sustainable and resilient buildings can result in increases of green walls and roofs in building infrastructure. This target can have synergies with the ability to invest in, conserve and enhance ecosystems in cities.	(Dunnett, 2006)
Goal 12. Ensure sustainable consumption and production patterns					
12.1	X	X		(A) Target calls for action on sustainable consumption and production also related to dimensions of the environment (B) Evidence of synergies between this target and the ability to invest in, conserve and enhance ecosystems in cities, e.g. food waste.	(Hall et al., 2009; UNEP, 2012a)

12.2	X	X		(A) Target requires changes in the use of natural resources in order to minimize impacts (B) Evidence that sustainable management of natural resources has synergies with the ability to invest in, conserve and enhance ecosystems in cities	(Newman, 1999)
12.3	X	X	X	(A) Target calls for reduction of global food waste which can include land-use changes to the environment in cities (B) Evidence of synergies and trade-offs between food waste and the ability to invest in, conserve and enhance ecosystems in cities. For example, increased composition facilities because food waste recycling can result in harmful effects to health. This can include organic material harvested from urban ecosystems.	As 12.1 (Douglas et al., 2016; Pearson et al., 2015)
12.4	X	X	X	(A) Target calls for sound management of wastes and reducing their release to the environment can affect the environment in cities (B) Evidence of synergies with the ability to invest in, conserve and enhance ecosystems in cities.	(Douglas et al., 2016; Gräslund and Bengtsson, 2001; Liu et al., 2008; Pearson et al., 2015; Van Der Werf, 1996)
12.5	X	X	X	(A) Target calls for reduction of waste generation which can result in de decline of environmental pollution ending up in the environment (B) Evidence of synergies and trade-offs between the waste reduction and the ability to invest in, conserve and enhance ecosystems in cities.	As 12.4 (Hischier et al., 2005; Liu et al., 2008)

12.6	X	X		(A) Target calls for action to encourage companies to adopt sustainable practices also related to the environment (B) Evidence that this target has synergies with the ability to invest in, conserve and enhance ecosystem in cities.	(Kolk, 2003; Labuschagne et al., 2005)
12.8	X	X		(A) Target calls for improving knowledge and skills on sustainable development including issues related to the environment (B) Evidence that promoting awareness for sustainable development has synergies with the ability of countries to invest in, conserve and enhance ecosystems in cities.	(Mittelstaedt et al., 1999; Perron et al., 2006)
12.a	X	X		(A) Target calls for support to strengthen scientific and technological capacity for consumption and production patterns, including related to the environment (B) Evidence of relationships between this target and the ability to invest in, conserve and enhance ecosystems in cities.	As 9.5
12.b	X	X	X	(A) Target calls for tools to monitor impacts of tourism, including related to the environment in cities (B) Evidence of the relationships between tourism and the ability to invest in, conserve and enhance ecosystems in cities.	(Cater, 1995; Clarke, 1997; Neto, 2003)
Goal 13. Take urgent action to combat climate change and its impacts					
13.1	X	X	X	(A) Target requires to modify the environment in cities to strengthen adaptive capacities to climate-related hazards (B) Evidence of synergies and trade-offs with the ability to invest in, conserve and enhance ecosystems in cities, e.g. protecting city populations from extreme heat waves through increasing vegetation cover to cool the city.	(Fezzi et al., 2015; Gill et al., 2007; Ürge-Vorsatz et al., 2014)

13.2	X	X	X	(A) Target stipulates integration of climate change measures into national policies, strategies and planning, which will include modifications to the environment in cities; as 13.1 (B) Evidence of synergies and trade-offs with the ability to invest in, conserve and enhance ecosystems in cities; e.g. as 13.1	As 13.1 (Pervin et al., 2013)
13.3	X	X	X	(A) Target stipulates to improve education and awareness-raising including topics that relate to the environment in cities (B) Evidence that capacity and awareness-raising on climate change will have synergies with the ability to invest in, conserve and enhance ecosystems in cities.	(Clark et al., 1997)
13.a		X	X	(B) Evidence that this target has synergies with the ability to invest in, conserve and enhance ecosystems in cities as the climate finance will contribute to climate adaptation projects which involve the environment in cities.	(Green Climate Fund, 2015a)
13.b		X	X	(B) Evidence that this target will have synergies with the ability of countries to invest in, conserve and enhance ecosystems in cities.	(Green Climate Fund, 2015b)
Goal 14. Conserve and sustainably use the oceans, seas and marine resources for sustainable development					
14.1	X	X		(A) Target calls for a reduction of marine pollution from land-based activities, which also relates to the environment in cities (B) Evidence that this target can affect the ability to invest in, conserve and enhance ecosystems in cities.	(Beman et al., 2005; Oberholster et al., 2008)

14.2	X	X	(A) Target calls for ecosystem-related outcomes, including coastal ecosystems or estuaries which are part of the environment of many cities (B) Evidence of synergies between this target with the ability to invest in, conserve and enhance ecosystems in cities.	(Rockefeller Foundation, 2013)
14.5	X	X	As 14.2	As 14.2
14.7	X	X	(A) Target calls for an increase of economic benefits from sustainable use of marine and coastal resources, which includes natural environments in cities (B) Evidence of synergies between this target and the ability to invest in, conserve and enhance ecosystems in cities.	(Mora et al., 2009)
14.c	X	X	(A) Target calls for implementation of international law through UNICLOS which includes natural environments in cities (B) Evidence of synergies between this target and the ability to invest in, conserve and enhance ecosystems in cities.	(UNICLOS, 1982)
Goal 15. Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss				
15.1	X	X	(A) This target calls for the conservation and restoration of terrestrial and inland freshwater ecosystems, including urban ecosystems (B) Evidence of synergies with the ability to invest in, conserve and enhance ecosystems in cities.	(Goddard et al., 2010)
15.2	X	X	As 15.1	(Rametsteiner and Simula, 2003)
15.3	X	X	As 15.1	(Stringer, 2008)

15.4	X	X	As 15.1	(Grêt-Regamey et al., 2012)
15.5	X	X	As 15.1	(Butchart et al., 2010; Yeung, 2001)
15.6	X	X	(A) Target calls for equitable sharing of genetic resources, including genetic resources in urban environments (B) Evidence of interlinkages between this target and the ability to invest in, conserve and enhance ecosystems in cities.	As 2.5
15.7	X	X	(A) Target calls to end poaching and trafficking of flora and fauna species, including species from urban ecosystems which are under intense anthropogenic pressure (B) Evidence of synergies between this target and the ability to invest in, conserve and enhance ecosystems in cities.	(CITES, 1973; Nellemann et al., 2016)
15.8	X	X	(A) Target calls to reduce the impact of invasive alien species, which are often first introduced in urban ecosystems through migration caused by international trade (B) Evidence of synergies between this target and the ability to invest in, conserve and enhance ecosystems in cities.	(Lowe S. et al., 2000; Pimentel et al., 2005; Rodriguez, 2006)
15.9	X	X	(A) This target calls to integrate ecosystem and biodiversity values into national and local planning and can impact planning on urban ecosystems overall (B) Evidence of synergies with the achievement of investing in, conserving and enhancing ecosystems in cities; e.g. the integration of ecosystem and biodiversity into national and local planning might affect how the environment is managed.	(ONS, 2017)

15.a	X	X	(A) Target calls for increases in financial resources to conserve urban ecosystems (B) Evidence of synergies between this target and the ability to invest in, conserve and enhance ecosystems in cities.	(WWF, 2007)
15.b	X	X	As 15.a	As 15.a
15.c	X	X	As 15.7	As 15.7
Goal 16. Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels				
16.3	X	X	(A) Targets calls for equal access to justice including environmental justice (B) Evidence of synergies between this target and the ability to invest in, conserve and enhance ecosystems in cities.	(López and Mitra, 2000; UNEP, 2012b)
16.5	X	X	(A) Target calls for reduction of corruption and bribery including corruption and bribery related to the environment (B) Evidence of synergies between this target and the ability to invest in, conserve and enhance ecosystems in cities.	As 16.3
16.6	X	X	(A) Target calls for accountable and transparent institutions which can influence environmental management in cities (B) Evidence of synergies between this target and the ability to invest in, conserve and enhance ecosystems in cities.	As 16.3

16.7	X	X		(A) Target calls for responsive and inclusive decision-making which includes decisions related to the environment (B) Evidence of synergies between this target and the ability to invest in, conserve and enhance ecosystems in cities.	(National Research Council, 2009)
16.8	X	X	X	(A) Target calls for strengthened participation of developing countries in global institutions which includes any institutions focusing on the environment in cities (B) Evidence of synergies and trade-offs between this target and the ability to invest in, conserve and enhance ecosystems in cities.	(Najam, 2005)
16.10	X	X		(A) Target calls for public access to information which includes environmental information (B) Evidence of synergies between this target and the ability to invest in, conserve and enhance ecosystems in cities.	(Haklay, 2003; Kingston et al., 2000)
16.b	X	X		(A) Target calls for non-discriminatory laws and policies on sustainable development which includes any policies on sustainable management of the environment in cities (B) Evidence of synergies between this target and the ability to invest in, conserve and enhance ecosystems in cities.	Probably link here but cannot find any evidence
Goal 17. Strengthen the means of implementation and revitalize the global partnership for sustainable development					
17.1	X	X	X	(A) Target inclusive of fiscal measures related to the environment (B) Evidence that resource mobilisation can affect the ability to invest in, conserve and protect the environment in cities.	(NEPAD and UNECA, 2014)

17.2	X	X	X	(A) Target inclusive of ODA/GNI development assistance commitments related to the environment (B) Evidence that manner of implementation of ODA commitments will have synergies and trade-offs with the ability to invest in, conserve and protect the environment in cities.	(Hicks et al., 2010)
17.3	X	X	X	(A) Target inclusive of resource mobilisation relating to the environment (B) Evidence that level of resource mobilisation will affect the ability to invest in, conserve and protect the environment in cities.	Same as 17.1
17.4	X	X	X	(A) Target inclusive of debt-related assistance and related measures concerning the environment. (B) Implementation of assistance will affect ability of developing countries to invest in, conserve and protect the environment in cities.	(Emerton et al., 2006)
17.5	X	X	X	(A) Target inclusive of investment-related actions relating to environment (B) Evidence that investment promotion will affect ability of least developed countries to invest in, conserve and protect the environment in cities.	(Wagner, 1999)
17.6	X	X	X	(A) Target inclusive of cooperation relating to environment (B) Evidence that cooperation will affect ability of relevant countries to invest in, conserve and protect the environment in cities.	(Metz et al., 2000)

17.7	X	X		(A) Target inclusive of technology-related measures concerning the environment (B) Evidence that promotion of environmentally sound technologies will have synergies with the ability of relevant countries to invest in, conserve and protect the environment in cities.	As 17.6
17.8	X	X	X	(A) Target inclusive of science and technology-related measures concerning the environment. (B) Relevant capacity building and other measures will affect the ability to invest in, conserve and protect the environment in cities.	Probably link here but cannot find any evidence
17.9	X	X	X	(A) Target inclusive of capacity building and collaboration relating to the environment in cities (B) Evidence that delivery of such activities will have synergies and trade-offs with the ability to invest in, conserve and protect the environment in cities.	(Ohiorhenuan and Wunker, 1995; Weidner et al., 2013)
17.14	X	X	X	(A) Target inclusive of actions to improve coherence of policies related to the environment (B) Evidence that level of policy coherence will affect efforts to invest in, conserve and protect the environment in cities.	(Nilsson et al., 2012)
17.15	X	X	X	(A) Target inclusive of policy implementation related to the environment (B) Evidence that policy development is important to the ability to invest in, conserve and enhance the environment in cities.	Probably link here but cannot find any evidence

17.16	X	X	X	(A) Target inclusive of partnership activities relating to the environment in cities (B) Evidence that partnerships are important to develop the environment in cities.	(De Sousa, 2003; Jim, 2004)
17.17	X	X	X	As 17.16	As 17.16
17.18	X	X		(A) Target inclusive of capacity-building activities related to the environment in cities (B) Evidence that environmental data is important to monitor the environment and dependent on capacity building efforts. Therefore, it has synergies with the ability to invest in, conserve and enhance ecosystems in cities.	(Günther, 1997; Pintér et al., 2000)
17.19	X	X		(A) Target inclusive of accounting efforts to natural capital (B) Measurements of progress complementary to national accounts, such as for example through the UN System for Environmental-Economic Accounting (UN SEEA), has synergies with the ability to invest in- conserve and enhance ecosystems in cities.	(ONS, 2015; UN, 2014a, 2014b)

Table A.2. Iterative qualitative conventional content analysis of Sustainable Development Goal (SDG) targets that call for action to urban ecosystems.

The content analysis contained three stages: (1) the wording of all identified SDG targets was individually summarised into a maximum set of three themes which can be either a word or a short sentence, (2) the themes in stage one were once again summarised into a maximum set of three themes for each SDG which again can be either a word or a short sentence, and (3) a final three key themes were identified for all SDGs together based on the themes of stage two. SDGs and SDG targets with no identified call for actions to urban ecosystems were excluded from this table.

SDG target	Stage 1	Stage 2	Stage 3
Goal 1. End poverty in all its forms everywhere			
1.4	- Equal rights to resources (economic, natural and financial) - All men and women, particularly the poor and vulnerable		
1.5	- Reduce exposure and vulnerability - Climate-related extreme events, environmental shocks, and disasters - Strengthen the poor and the vulnerable	- Equal rights and mobilisation of resources - Protect the poor and the vulnerable - End poverty in all dimensions	- Sustainable management of biodiversity, ecosystems, and natural resources - Equal rights to basic services for all and the pursuit of economic growth - Multilevel governance and policy development through capacity building and international cooperation
1.a	- Mobilisation of resources - Implement policies and programmes that end poverty in all dimensions		
Goal 2. End hunger, achieve food security and improved nutrition, and promote sustainable agriculture			
2.1	- End hunger - Access to nutritious and sufficient food - Particularly the poor and the vulnerable	- End hunger, including through nutritious food - Sustainable and resilient agricultural practices - Maintain and share genetic resources	
2.3	- Double agricultural productivity and incomes of small-scale food producers - Small-scale food producers		
2.4	- Ensure sustainable food production systems - Implement resilient agricultural practices		

2.5	- Maintain genetic diversity of plants and animals - Promote access and sharing of the benefits of genetic resources	
Goal 3. Ensure healthy lives and promote wellbeing for all at all ages		
3.9	- Reduce deaths and illnesses - Hazardous chemicals, air, water and soil	- Manage health risks - Strengthen health systems - Environmental pollution and contamination
3.c	- Increase health financing - Increase health workforce	
3.d	- Strengthen capacity for early warning and risk reduction - National and global health risks	
Goal 4. Ensure inclusive and equitable quality education and promote life-long learning opportunities for all		
4.7	- Promote knowledge and skills on sustainable development - All learners	- Promote education on sustainable development
4.b	- Expand scholarships in higher education globally - Developing countries	
Goal 6. Ensure availability and sustainable management of water and sanitation for all		
6.1	- Safe and affordable drinking water - Universal and equitable access	- Provide drinking water and sanitation for all - Sustainable and integrated water management - Capacity building through international cooperation and local communities
6.2	- Provide sanitation and hygiene for all - End open defecation	
6.3	- Improve water quality - Halve proportion of untreated wastewater - Increase recycling and reuse of water	
6.4	- Increase water-use efficiency - Sustainable management of freshwater - Reduce water scarcity	
6.5	- Integrated water management	

6.6	- Protect and restore water-related ecosystems	
6.a	- Expand international cooperation and capacity-building - Developing countries	
6.b	- Strengthen local communities - Water and sanitation management	
Goal 7. Ensure access to affordable, reliable, sustainable and modern energy for all		
7.1	- Universal access to modern energy services	
7.2	- Share of renewable energy - Global energy mix	- Equal access to energy services - Increase renewables
7.b	- Expand energy infrastructure - Developing countries	- Develop and upgrade energy infrastructure
Goal 8. Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all		
8.1	- Sustain economic growth	
8.2	- Increase economic productivity	- Sustainable economic growth - Resource efficiency
8.4	- Improve resource efficiency - Decouple economic growth from environmental degradation	
Goal 9. Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation		
9.1	- Develop resilient infrastructure - Affordable and equitable access - Support economic development and human well-being	- Develop and modernise infrastructure - Encourage scientific research, innovation and technological development
9.4	- Upgrade infrastructure - Adapt industries - Environmentally sound technologies and processes	

9.5	- Scientific research - Technological capabilities - Encouraging innovation	
9.a	- Resilient infrastructure - Financial, technological and techincal support - Developing countries	
Goal 10. Reduce inequality within and among countries		
10.b	- Encourage development assistance and financial flows - Developing countries	- Encourage development assistance and financial flows
Goal 11. Make cities and human settlements inclusive, safe, resilient and sustainable		
11.1	- Upgrade slums - Affordable housing and basic services	
11.2	- Access to sustainable transport systems - Improve road safety	
11.3	- Inclusive and sustainable urbanisation - Participation in planning and management	
11.4	- Protect cultural and natural heritage	
11.5	- Reduce casualties - Decrease direct economic losses - Disasters	- Sustainable urban development through inclusivity, affordability and accessibility - Strengthen policies and plans at all levels - Reduce environmental impact
11.6	- Reduce environmental impact - Cities	
11.7	- Universal access to green and public spaces - Particularly the poor and vulnerable	
11.a	- Support environmental links between urban and rural areas - Strengthen national and regional development planning	

11.b	- Implement integrated policies and plans - Disaster risk management	
Goal 12. Ensure sustainable consumption and production patterns		
12.1	- Implement programmes on sustainable consumption and production - All countries take action	- Protect and efficiently use natural resources - Reduce environmental impact through sounds management - Develop a sustainability reporting culture in companies
12.2	- Sustainable management of natural resources - Efficient use of natural resources	
12.3	- Halve global food waste - Reduce food losses	
12.4	- Sound environmental management of chemicals and wastes - Reduce release of chemicals and wastes into environment	
12.5	- Reduce waste generation	
12.6	- Adopt sustainable practices - Integrate sustainability information	
12.8	- Information and awareness on sustainable development	
12.a	- Sustainable patterns of consumption and production - Strengthen scientific and technological capacity - Support developing countries	
12.b	- Sustainable tourism - Monitor sustainable development impacts	
Goal 13. Take urgent action to combat climate change and its impacts		
13.1	- Hazards and disasters - Strengthen resilience - Strengthen adaptive capacity	- Combat and adapt to climate change - Increase resilience to environmental hazards and disasters

13.2	- Climate change measures - National policies, strategies and planning	
13.3	- Education and awareness-raising - Human and institutional capacity - Climate change and risk reduction	
Goal 14. Conserve and sustainably use the oceans, seas and marine resources for sustainable development		
14.1	- Reduce marine pollution - Land-based activities	
14.2	- Sustainably manage and restore marine and coastal ecosystems	- Protect and restore marine and coastal areas - Sustainably use marine and coastal resources
14.5	- Conserve 10% marine and coastal areas	
14.7	- Sustainable use of marine resources - Increase economic benefits	
14.c	- Conserve oceans - Sustainable use of oceans and their resources - Implement international law	
Goal 15. Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss		
15.1	- Conserve and restore terrestrial and inland freshwater ecosystems and services - International agreements	- Conserve and sustainably use terrestrial and freshwater biodiversity and ecosystems - Combat illegal activities of poaching and trafficking of wildlife - Incorporate nature valuation in all levels of governance and mobilise resources from all sources
15.2	- Sustainably manage forests - Halt deforestation - Increase reforestation	
15.3	- Combat desertification - Restore degraded land and soil - Develop a land-degradation neutral world	
15.4	- Conserve mountain ecosystems	

15.5	- Reduce the degradation of natural habitats - Halt the loss of biodiversity - Protect and prevent the extinction of threatened species	
15.6	- Utilisation of genetic resources - Fair, and equitable access to genetic resources	
15.7	- End poaching and trafficking of protection species - Illegal wildlife products	
15.8	- Prevent introduction of invasive alien species - Control or eradicate priority species	
15.9	- Ecosystem and biodiversity values - National and local strategies, planning and processes	
15.a	- Increase financial resources - Conserve and sustainably use biodiversity and ecosystems	
15.b	- Mobilise resources from all sources - Sustainable forest management - Provide incentives to advance forest management	
15.c	- Combat poaching and trafficking of threatened species - Pursue sustainable livelihood opportunities	
Goal 16. Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels		
16.3	- Promote rule of law - Equal access to justice	- Transparent and accountable institutions at all levels with representative decision-making
16.5	- Reduce corruption - Reduce bribery	

16.6	- Effective, accountable and transparent institutions at all levels	- Non-discriminatory rule of law and justice for all
16.7	- Responsive, inclusive and representative decision-making - At all levels of governance	
16.8	- Strengthen participation of developing countries - Institutions of global governance	
16.10	- Protect fundamental freedoms - Public access to information	
16.b	- Non-discriminatory laws and policies	
Goal 17. Strengthen the means of implementation and revitalize the global partnership for sustainable development		
17.1	- Strengthen resource mobilisation - Improve tax and other revenue collection	
17.2	- Implement official development assistance commitments	- Sustainably mobilise and manage debt and financial resources in countries - Transfer and operationalise technologies and other resources - Increase international cooperation and partnerships, and enhance capacity-building on all levels for developing countries - Encourage policy coherence on sustainable development with respect to each country's leadership
17.3	- Mobilise financial resources	
17.4	- Attain long-term debt sustainability - Address the external debt - Reduce debt distress	
17.5	- Investment promotion regimes	
17.6	- Enhance international cooperation - Enhance knowledge-sharing - Access to science, technology and innovation	
17.7	- Promote development, transfer, dissemination and diffusion of environmentally sound technologies	

17.8	- Enhance the use of enabling technology - Operationalise technology and innovation-capacity building mechanism
17.9	- Enhance capacity-building - International cooperation
17.14	- Policy coherence - Sustainable development
17.15	- Policy space and leadership - Policies for poverty eradication - Policies for sustainable development
17.16	- Global partnership on sustainable development - Multi-stakeholder partnerships - Share resources (financial, technology, ...)
17.17	- Promote partnerships
17.18	- Capacity-building - Developing countries - National contexts
17.19	- Sustainable development indicators - Gross-domestic product - Capacity-building

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Appendix B

Methods 1: longitudinal analysis

Executive function (EF)

I treated the EF as a continuous variable and I therefore modelled the outcome EF with a Gaussian distribution. I started by specifying Y_{ij}^{EF} as the measured composite score of three cognitive tests (i.e. Backward Digit Span, Spatial Working Memory and Trail Making Task) measured during the first and second visit. As the EF was characterized by tests with different scales, the tests were z-standardized to make them comparable:

$$z_i = \frac{x_i - \mu}{\sigma} \quad (1)$$

As Y_{ij}^{EF} was a continuous variable and can assume any value after standardization, it was reasonable to assume a Gaussian distribution with $j = 1, 2$ (time of first and second visit) and $i = 1, \dots, I = 3{,}568$ (total number of adolescents in this study):

$$Y_{ij}^{EF} \sim N(\mu_{ij}^{EF},\ \sigma_{EF}^2) \quad (2)$$

where σ_{EF}^2 was the variance. On μ_{ij}^{EF}, we specified a linear model:

$$\mu_{ij}^{EF} = \beta_0 + \eta_{ij} + \beta_1 X_{ij}^{age} + \beta_2 X_{ij}^{air} + \beta_3 X_{ij}^{area} + \beta_4 X_i^{ethn} + \beta_5 X_i^{gender} + \beta_6 X_{ij}^{ecotyp} + \beta_7 X_i^{par} + \beta_8 X_i^{schtyp} + \varepsilon_i \quad (3)$$

where β_0 was the global intercept, $\beta_1, \dots, \beta_8$ were the regression coefficients associated with the covariates, ε_i was the random effect for adolescent i and η_{ij} was the random effect for time j nested in adolescent i. Age = adolescent's age; air = air pollution; area = area-level deprivation; ethn = ethnicity; gender = adolescent's gender; ecotyp = urban ecosystem type; par = parental occupation; schtyp = school type.

Strengths and Difficulties Questionnaire (SDQ) total difficulties score

I treated SDQ total difficulties score as count data and I therefore modelled the outcome SDQ total difficulties score with a Poisson distribution. I started by

specifying Y_{ij}^{TDS} as the observed number of behavioral difficulties with $j = 1, 2$ (time of first and second visit) and $i = 1, \dots, I = 3{,}568$ (total number of adolescents in this study) and specified the Poisson model:

$$Y_{ij}^{TDS} \sim Poisson\ (\lambda_{ij}^{TDS}\ E_{ij}^{TDS}) \tag{4}$$

where E_{ij}^{TDS} represented the expected number of behavioral difficulties (included in the model as an offset in the log scale) and λ_{ij}^{TDS} represented the log relative risk of behavioral difficulties. I therefore specified a regression model on the log link transformed λ_{ij}^{TDS}:

$$log\ (\lambda_{ij}^{TDS}) = \beta_0 + \eta_{ij} + \beta_1 X_{ij}^{age} + \beta_2 X_{ij}^{area} + \beta_3 X_i^{ethn} + \beta_4 X_i^{gender} + \beta_5 X_{ij}^{nattyp} + \beta_6 X_i^{par} + \beta_7 X_i^{schtyp} + \varepsilon_i \tag{5}$$

where β_0 was the global intercept, $\beta_1, \dots, \beta_7$ were the regression coefficients associated with the covariates, ε_i was the random effect for adolescent i and η_{ij} was the random effect for time j nested in adolescent i.

KIDSCREEN-10 Health-Related Quality of Life (HRQoL) score

I modelled our binary outcome KIDSCREEN-10 Questionnaire HRQoL score with a Binomial distribution with $j = 1, 2$ (time of first and second visit) and $i = 1, \dots, I = 3{,}568$ (total number of adolescents in this study). I modelled the probability of low overall well-being p_{ij} of adolescent i at time j using the logit link function:

$$\text{logit}(p_{ij}) = log\ (\tfrac{p_{ij}}{1-p_{ij}}) = \beta_0 + \eta_{ij} + \beta_1 X_{ij}^{age} + \beta_2 X_{ij}^{area} + \beta_3 X_i^{ethn} + \beta_4 X_i^{gender} + \beta_5 X_{ij}^{nattyp} + \beta_6 X_i^{par} + \beta_7 X_i^{schtyp} + \varepsilon_i \tag{6}$$

where β_0 was the global intercept, $\beta_1, \dots, \beta_7$ were the regression coefficients associated with the covariates, ε_i was the random effect for adolescent i and η_{ij} was the random effect for time j nested in adolescent i.

Methods 2: cross-sectional analysis

Executive function (EF)

I specified Y_{ij}^{EF} as the measured composite score of three cognitive tests measured during the first visit at the schools. As Y_{ij}^{EF} was a continuous variable, and after standardization it can assume any value in $\mathbb{R}$, it was reasonable to assume the following Gaussian distribution with $j = 1, \dots, J = 39$ (total number of schools) and $i = 1, \dots, I = 6{,}386$ (total number of adolescents):

$$Y_{ij}^{EF} \sim N(\mu_{ij}^{EF},\ \sigma_{EF}^2) \tag{7}$$

where σ_{EF}^2 was the variance. We therefore specified a linear model for μ_{ij}^{EF}:

$$\mu_{ij}^{EF} = \beta_0 + \eta_{ij} + \beta_1 X_i^{age} + \beta_2 X_i^{air} + \beta_3 X_i^{area} + \beta_4 X_i^{ethn} + \beta_5 X_i^{gender} + \beta_6 X_i^{ecotyp} + \beta_7 X_i^{par} + \beta_8 X_i^{schtyp} \tag{8}$$

where β_0 was the EF global intercept, $\beta_1, \dots, \beta_8$ were the regression coefficients associated with the covariates and η_{ij} was the random effect for school j with adolescent i. Age = adolescent's age; air = air pollution; area = area-level deprivation; ethn = ethnicity; gender = adolescent's gender; ecotyp = urban ecosystem type; par = parental occupation; schtyp = school type.

Strengths and Difficulties Questionnaire (SDQ) total difficulties score

I modelled our outcome SDQ total difficulties score with a Poisson distribution. I started by specifying Y_{ij}^{TDS} as the observed number of behavioral difficulties with $j = 1, \dots, J = 39$ (total number of schools) and $i = 1, \dots, I = 6{,}386$ (total number of adolescents), and treated these variables as count data to specify the Poisson model:

$$Y_{ij}^{TDS} \sim Poisson\ (\lambda_{ij}^{TDS}\ E_{ij}^{TDS}) \tag{9}$$

where E_{ij}^{TDS} represented the expected number behavioral difficulties and λ_{ij}^{TDS} represented the relative risk of behavioral difficulties. I therefore specified a regression model on the log link transformed λ_{ij}^{TDS}:

$$\log(\lambda_{ij}^{TDS}) = \beta_0 + \eta_{ij} + \beta_1 X_i^{age} + \beta_2 X_i^{area} + \beta_3 X_i^{ethn} + \beta_4 X_i^{gender} + \beta_5 X_i^{nattyp} + \beta_6 X_i^{par} + \beta_7 X_i^{schtyp} + \varepsilon_i \quad (10)$$

where β_0 is the global intercept, $\beta_1, \dots, \beta_7$ were the regression coefficients associated with the covariates, η_{ij} was the random effect for school j with adolescent i, and ε_i was the random effect for adolescent i. I included an additional random effect $\varepsilon_i \sim N(0, \sigma_\varepsilon^2)$ for adolescent i to account for overdispersion, which is typically present when using a Poisson model(Blangiardo et al., 2019).

KIDSCREEN-10 Health-Related Quality of Life (HRQoL) score

I modelled our binary outcome KIDSCREEN-10 Questionnaire HRQoL score with a Binomial distribution with $j = 1, \dots, J = 39$ (total number of schools) and $i = 1, \dots, I =$ 6,386 (total number of adolescents). I modelled the probability of low overall wellbeing p_{ij} of adolescent i at school j using the logit link function:

$$\text{logit}(p_{ij}) = log\left(\frac{p_{ij}}{1-p_{ij}}\right) = \beta_0 + \eta_{ij} + \beta_1 X_i^{age} + \beta_2 X_i^{area} + \beta_3 X_i^{ethn} + \beta_4 X_i^{gender} + \beta_5 X_i^{nattyp} + \beta_6 X_i^{par} + \beta_7 X_i^{schtyp} \quad (11)$$

where β_0 was the global intercept, $\beta_1, \dots, \beta_7$ were the regression coefficients associated with the covariates and η_{ij} was the random effect for school j with adolescent i.

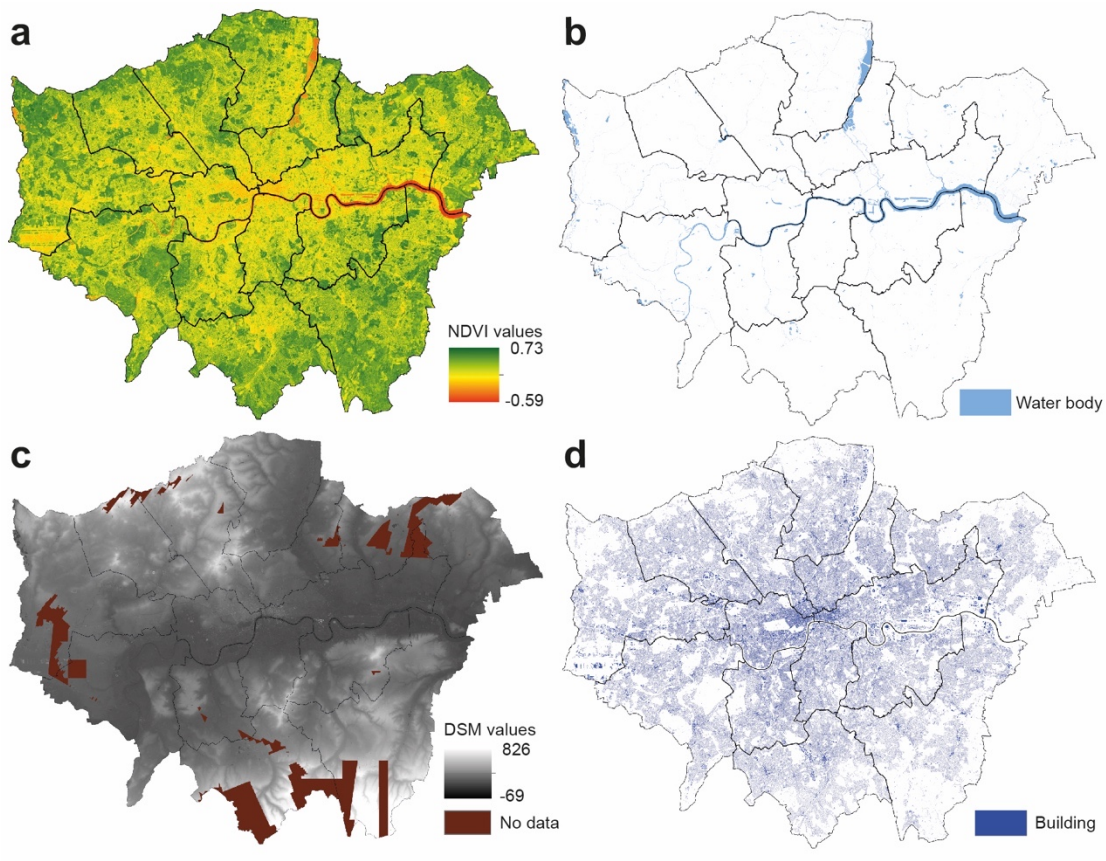

Figure B.1. Environmental datasets used to quantify the type of urban ecosystem exposure.

(a) Normalised Difference Vegetation Index developed using Sentinel-2 satellite data through Google Earth Engine (earthengine.google.com), (b) combined surface and tidal water body layer from the Ordnance Survey (OS) Open Map available at ordnancesurvey.co.uk, (c) airborne Light Detection and Ranging layer of the Digital Surface Model from the Environment Agency available at data.gov.uk and (d) buildings map from the OS Open Map (all images in this figure were restricted to the area of Greater London for visualization purposes).

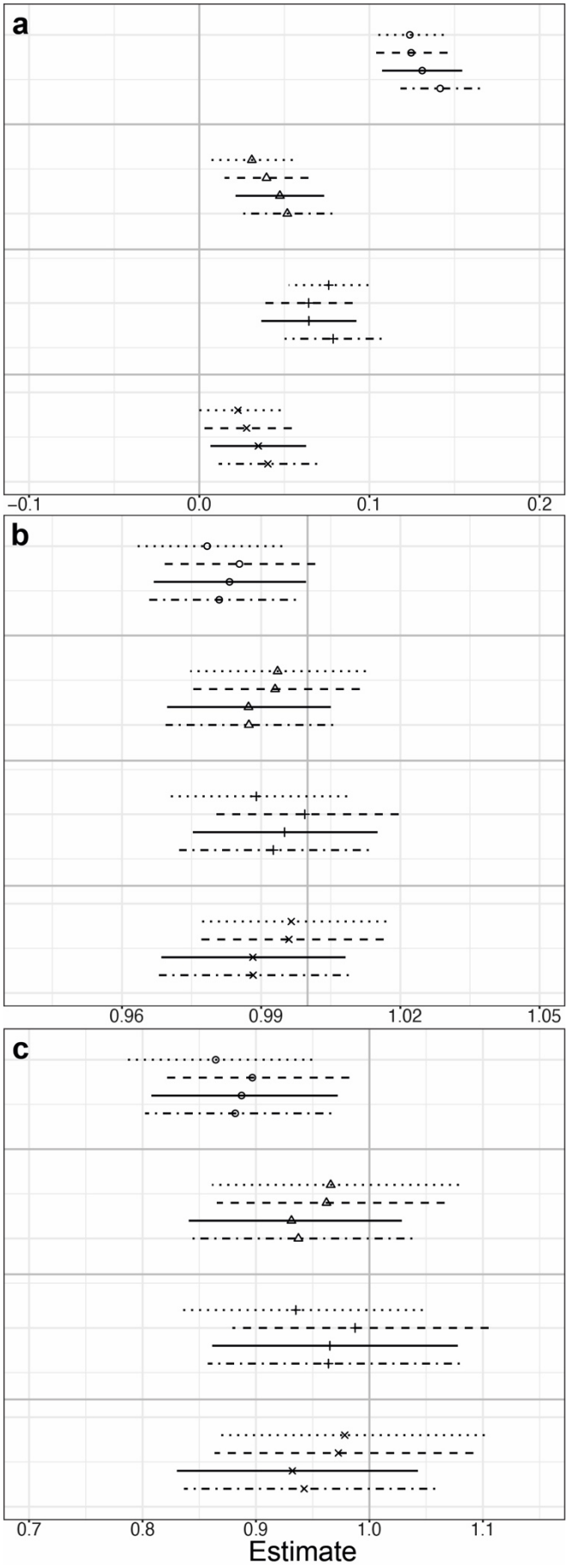

Figure B.2. Comparison of different buffer areas to investigate the association between natural space daily exposure rate (DER) and cognitive development, mental health and overall well-being during adolescence.

The association between (a) executive function (EF) score, (b) Strengths and Difficulties Questionnaire (SDQ) total difficulties score (TDS) and (c) KIDSCREEN-10 Questionnaire Health-Related Quality of Life (HRQoL) score with natural space DER in buffer areas of 50 m (dotted line), 100 m (dashed line), 250 m (solid line) and 500 m (dotdash line) around the residential and school area. Four models were fitted:
(○) unadjusted (△) adjusted for the effect of ethnicity and school type, (+) adjusted for socio-economic factors which includes area-level deprivation and parental occupation and (×) adjusted for all factors which includes area-level deprivation, ethnicity, parental occupation and school type. All four models were adjusted for age and gender, in the case of EF additionally adjusted for air pollution, and plotted with posterior mean and 95% credible intervals (CI). The vertical line (in grey) is the reference line and significance can be deduced when the 95% CI excludes zero for the EF, and

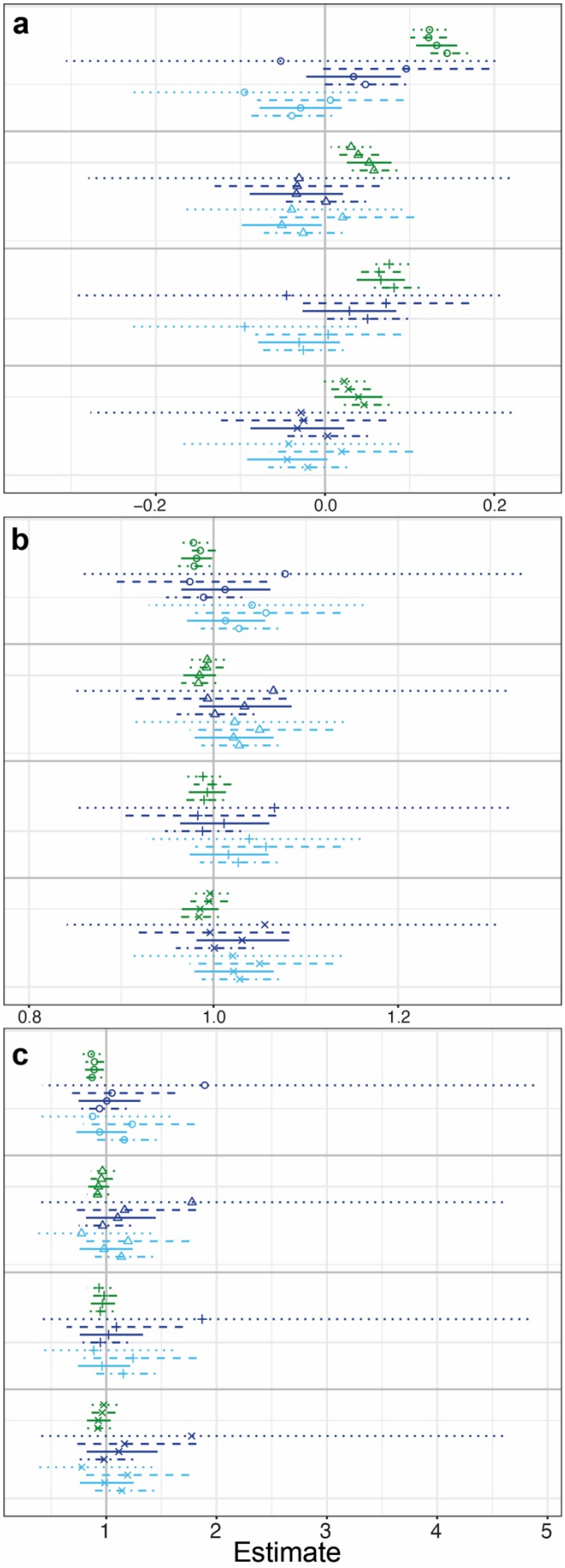

Figure B.3. Comparison of different buffer areas to investigate the association between green and blue space daily exposure rate (DER), and cognitive development, mental health and overall well-being during adolescence.

The association between (a) executive function (EF) score, (b) Strengths and Difficulties Questionnaire (SDQ) total difficulties score (TDS) and (c) KIDSCREEN-10 Questionnaire Health-Related Quality of Life (HRQoL) score with the DER of green space (●), blue space level 2 (●) and blue space level 3 (●) in buffer areas of 50 m (dotted line), 100 m (dashed line), 250 m (solid line) and 500 m (dotdash line) around the residential and school area. Four models were fitted: (○) unadjusted (△) adjusted for the effect of ethnicity and school type, (+) adjusted for socio-economic factors which includes parental occupation and area-level deprivation and (×) adjusted for all factors which includes ethnicity, school type, parental occupation and area-level deprivation. All four models were adjusted for age and gender, in the case of EF additionally adjusted for air pollution, and plotted with posterior mean and 95% credible intervals (CI). The vertical line (in grey) is the reference line and significance can be deduced when the 95% CI excludes zero for the EF, and excludes one for the SDQ TDS and HRQoL score.

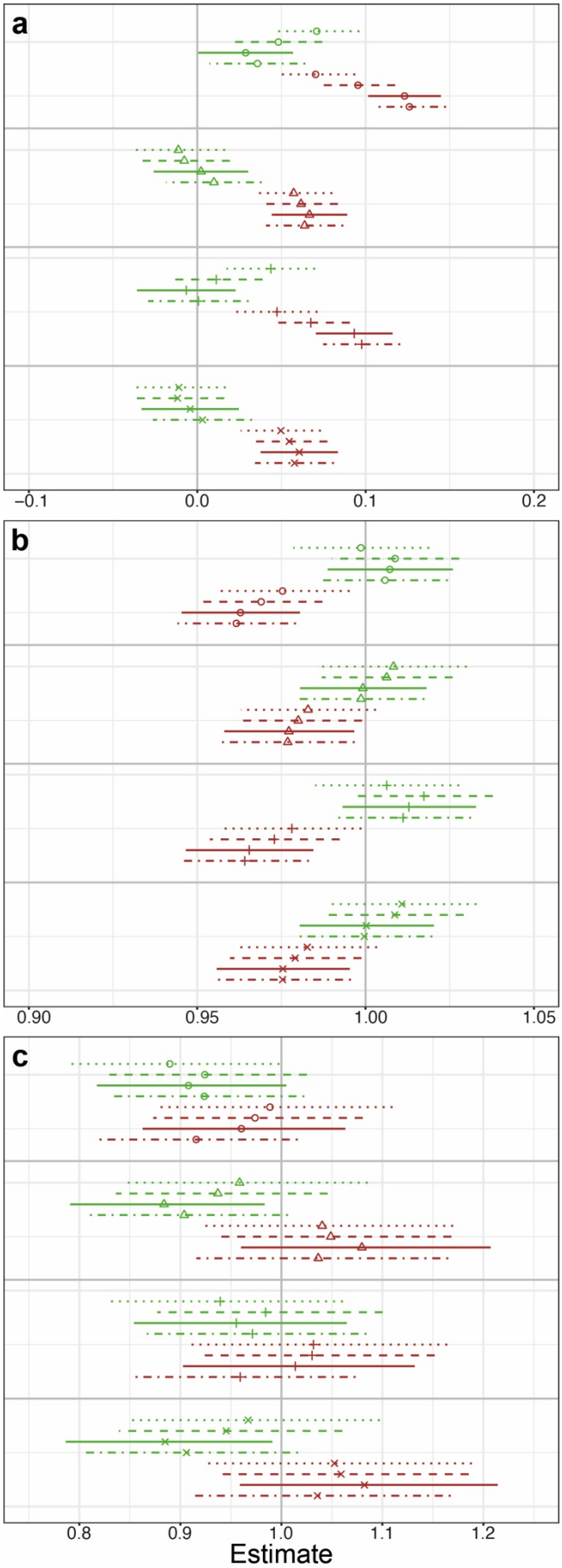

Figure B.4. Comparison of different buffer areas to investigate the association between grassland and woodland daily exposure rate (DER), and cognitive development, mental health and overall well-being during adolescence.

The association between (a) executive function (EF) score, (b) Strengths and Difficulties Questionnaire (SDQ) total difficulties score (TDS) and (c) KIDSCREEN-10 Questionnaire Health-Related Quality of Life (HRQoL) score with the DER of grassland (●) and woodland (●) in buffer areas of 50 m (dotted line), 100 m (dashed line), 250 m (solid line) and 500 m (dotdash line) around the residential and school area. Four models were fitted: (○) unadjusted, (△) adjusted for the effect of ethnicity and school type, (+) adjusted for socio-economic factors which includes parental occupation and area-level deprivation and (×) adjusted for all factors which includes ethnicity, school type, parental occupation and area-level deprivation. All four models were adjusted for age and gender, in the case of EF additionally adjusted for air pollution, and plotted with posterior mean and 95% credible intervals (CI). The vertical line (in grey) is the reference line and significance can be deduced when the 95% CI excludes zero for the EF, and excludes one for the SDQ TDS and HRQoL score.

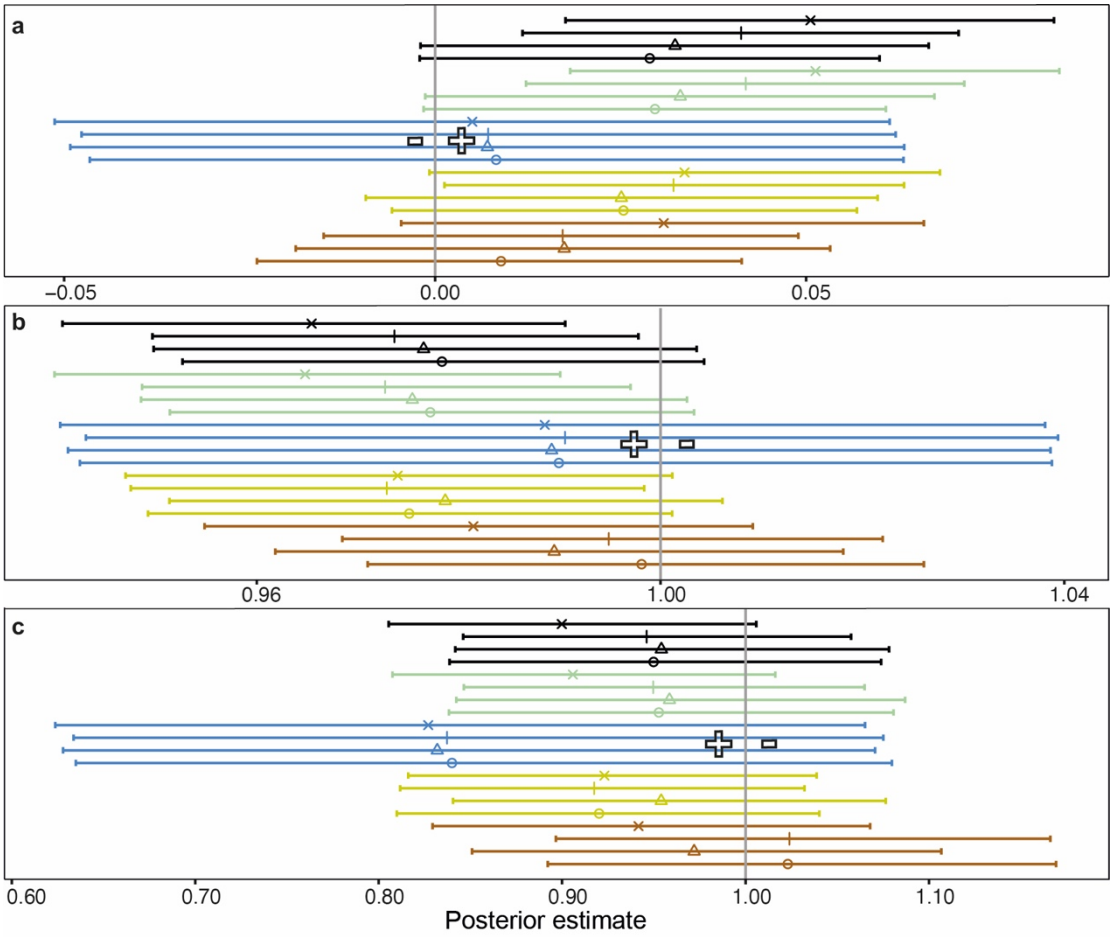

Figure B.5. Cross-sectional analysis of the associations between urban ecosystem type daily exposure rate (DER), and cognitive performance, mental health and overall well-being across London.

The association between the (a) executive function (EF) score, (b) Strengths and Difficulties Questionnaire total difficulties score and (c) KIDSCREEN-10 Questionnaire Health-Related Quality of Life score with the urban ecosystem type DER of Model I: natural space (—●—), Model II: green space (—●—), blue space level 3 (—●—), and Model III: grassland (—●—) and woodland (—●—). We only represented blue space level 3 in this figure. Four models were fitted: (○) unadjusted (△) adjusted for the effect of ethnicity and school type, (+) adjusted for socio-economic factors which includes parental occupation and area-level deprivation and (×) adjusted for all factors which includes ethnicity, school type, parental occupation and area-level deprivation. All four models were adjusted for age and gender, plotted with 95% credible intervals (CI), and models with EF as the outcome were additionally adjusted for air pollution. The vertical line (in grey) is the reference line and is set to zero or one depending on the probability distribution used in each model (Appendix D Methods 2). Hollow plus or minus sign indicated whether the association had a positive or negative contribution towards high cognitive performance / good mental health vs. low cognitive performance / poor mental health.

Table B.1. Cohort characteristics during the first (t_0) and second (t_1) school visit.

Data from t_0 and t_1 were based on participants who took part in the computer-based assessment. This study used a subset of adolescents (n = 3,568) who had a known residence address during t_0 and t_1 (Table 1). Parental occupation is based on the highest National Statistics Socio-economic Classification (NS-SEC) level (five-group version) of either parent. Qn1, Qn2, Qn3, Qn4 and Qn5 of area-level deprivation represented the first, second, third, fourth and fifth quintile of the Carstairs deprivation index, respectively.

	First school visit		Second school visit	
	n = 6,612		n = 5,208	
	Median	IQR	Median	IQR
Age (years)	12.06	11.78-12.33	14.21	13.92-14.56
Parental occupation	n	%	n	%
Managerial/professional occupations	3270	49.45	2788	53.53
Intermediate occupations	484	7.32	283	5.43
Small employers/own-account workers	908	13.73	752	14.43
Lower supervisory/technical occupations	272	4.11	190	3.64
Semi-routine/routine occupations	693	10.48	397	7.62
Missing/not interpretable	985	14.89	798	15.32
Area-level deprivation				
Least deprived (Qn1)	919	13.89	821	15.76
Qn2	944	14.27	810	15.55
Qn3	1122	16.96	873	16.76
Qn4	1389	21	1050	20.16
Most deprived (Qn5)	2024	30.61	1495	28.70
Missing	214	3.23	159	3.05
Gender				
Female	3468	52.45	2823	54.20
Male	3144	47.54	2385	45.79
Ethnicity				
White	2719	41.12	2265	43.49
Black	980	14.82	739	14.18
Asian	1715	25.93	1354	25.99
Mixed	712	10.76	498	9.56
Other/not interpretable	54	0.81	28	0.53
Missing	432	6.53	324	6.22
Type of school				
State	5177	78.29	3918	75.23
Independent	1435	21.70	1290	24.76

Table B.2. Median (Q1-Q3) and Pearson's correlation coefficient between estimates of air pollution daily exposure rate (DER).

	n	Median (Q1-Q3)	NO_2 DER	NO_x DER	PM_{10} DER	$PM_{2.5}$ DER
NO_2 DER	3,305	35.69 (33.41-38.23)	1	0.98	0.95	0.98
NO_x DER	3,305	63.46 (57.19, 70.54)		1	0.96	0.96
PM_{10} DER	3,305	6.92 (5.88-8.11)			1	0.95
$PM_{2.5}$ DER	3,305	13.17 (12.84-13.51)				1

Table B.3. Median (Q1-Q3) and Pearson's correlation coefficient between estimates of urban ecosystem type daily exposure rate (DER).

			Natural	Green	Blue space DER				
	n	Median (Q1-Q3)	space DER	space DER	Level 1 (ref)	Level 2	Level 3	Grassland DER	Woodland DER
Natural space DER	3,563	0.53 (0.37, 0.67)	1	0.99	-	-	-	0.94	0.63
Green space DER	3,563	0.53 (0.36, 0.67)		1	-	-	-	0.95	0.64
Blue space DER									
Level 1 (ref)	2,383	-			1	-	-	-	-
Level 2	473	-				1	-	-	-
Level 3	707	-					1	-	-
Grassland DER	3,367	0.38 (0.25, 0.49)						1	0.38
Woodland DER	3,367	0.06 (0.04, 0.11)							1

Table B.4. Cross validation results testing different models for the executive function (EF) score.

I tested Gaussian models with different random effect (RE) structures between the EF score and natural space daily exposure rate during adolescence. I used model-selection criteria to identify the best model, i.e. the Deviance Information Criterion (DIC), the Log-Pseudo Marginal Likelihood (LPML) and the pseudo R-squared from 10-fold cross validation where a lower DIC and a higher LPML and pseudo-R squared better support the data. I added penalized complexity priors to models with an asterisk (*) because the precision of the model hyperparameters was far too high with the default prior (Simpson et al., 2017). I used the standard deviation of the residuals of the fixed effects only model to specify a scale for the standard deviation of the random effects.

	Unadjusted	Adjusted for ethnicity and school type	Adjusted for socio-economic status	Adjusted for all
DIC				
No RE	12247	11900	12150	11894
RE for adolescent id	9579	9479	9567	9481
RE for school type	11958	11900	11952	11894
RE for school id	11785	11740	11792	11748
RE for adolescent id and school id	9497	9469	9501	9474
RE for time of visit	12118	11771	12020	11763
*RE for adolescent id and time of visit (2-level nested model)	6509	6451	6509	6453
*RE for school id, adolescent id, time of visit (3-level nested model)	6375	-1927	6363	-36204
LPML				
No RE	-6123	-5950	-6075	-5947
RE for adolescent id	-5157	-5075	-5142	-5076
RE for school type	-5979	-5950	-5976	-5947
RE for school id	-5892	-5870	-5896	-5874
RE for adolescent id and school id	-5070	-5052	-5074	-5056
RE for time of visit	-6059	-5885	-6010	-5881
*RE for adolescent id and time of visit (2-level nested model)	-5156	-5075	-5141	-5076
*RE for school id, adolescent id, time of visit (3-level nested model)	-5070	-5021	-5073	12822
Pseudo R-squared from 10-fold cross validation				
No RE	0.21	0.31	0.25	0.31
RE for adolescent id	0.89	0.88	0.89	0.88
RE for school type	0.29	0.31	0.30	0.31
RE for school id	0.35	0.36	0.35	0.36
RE for adolescent id and school id	0.88	0.88	0.88	0.88
RE for time of visit	0.25	0.34	0.29	0.35
*RE for adolescent id and time of visit (2-level nested model)	0.98	0.98	0.98	0.98
*RE for school id, adolescent id, time of visit (3-level nested model)	0.98	0.99	0.98	1

Table B.5. Cross validation results testing different models for the Strengths and Difficulties Questionnaire (SDQ) total difficulties score.

I tested Poisson models with different random effect (RE) structures between the SDQ total difficulties score and natural space daily exposure rate during adolescence. I used model-selection criteria to identify the best model, i.e. the Deviance Information Criterion (DIC), the Log-Pseudo Marginal Likelihood (LPML) and the pseudo R-squared from 10-fold cross validation where a lower DIC and a higher LPML and pseudo-R squared better support the data.

	Unadjusted	Adjusted for ethnicity and school type	Adjusted for socio-economic status	Adjusted for all
DIC				
No RE	43009	42765	42948	42748
RE for adolescent id	35036	35033	35041	35035
RE for school type	42884	42764	42865	42748
RE for school id	42527	42462	42522	42456
RE for adolescent id and school id	35026	35025	35027	35026
RE for time of visit	42795	42542	42735	42530
RE for adolescent id and time of visit (2-level nested model)	34555	34550	34559	34553
RE for school id, adolescent id, time of visit (3-level nested model)	34542	34541	34545	34543
LPML				
No RE	-21509	-21391	-21486	-21390
RE for adolescent id	-18439	-18431	-18445	-18435
RE for school type	-21447	-21391	-21445	-21390
RE for school id	-21294	-21264	-21299	-21269
RE for adolescent id and school id	-18424	-18421	-18428	-18424
RE for time of visit	-21402	-21281	-21380	-21282
RE for adolescent id and time of visit (2-level nested model)	-18213	-18203	-18218	-18208
RE for school id, adolescent id, time of visit (3-level nested model)	-18195	-18192	-18200	-18196
Pseudo R-squared from 10-fold cross validation				
No RE	0.05	0.13	0.08	0.13
RE for adolescent id	0.87	0.87	0.87	0.87
RE for school type	0.09	0.13	0.11	0.14
RE for school id	0.18	0.19	0.18	0.20
RE for adolescent id and school id	0.87	0.87	0.87	0.87
RE for time of visit	0.12	0.17	0.13	0.17
RE for adolescent id and time of visit (2-level nested model)	0.96	0.96	0.96	0.96
RE for school id, adolescent id, time of visit (3-level nested model)	0.96	0.96	0.96	0.96

Table B.6. Cross validation results testing different models for the KIDSCREEN-10 Questionnaire Health-Related Quality of Life (HRQoL) score.

I tested Binomial models with different random effect (RE) structures between the HRQoL score and natural space daily exposure rate during adolescence. I used model-selection criteria to identify the best model, i.e. the Deviance Information Criterion (DIC) and the Log-Pseudo Marginal Likelihood (LPML) where a lower DIC and a higher LPML better support the data. I did not use 10-fold cross validation because the observed value is binomial, making it impossible to calculate a pseudo R-squared. I added informative gamma priors to models with an asterisk (*) because the precision of model parameters was far too high with the default prior. I set the mean value of the gamma prior to the inverse of the variance of the residuals of the fixed-effects only model.

	Unadjusted	Adjusted for ethnicity and school type	Adjusted for socio-economic status	Adjusted for all
DIC				
No RE	4013	3970	4018	3980
RE for adolescent id	3843	3805	3840	3807
*RE for school type	3996	3970	4006	3979
*RE for school id	4004	3971	4013	3980
*RE for adolescent id and school id	3819	3789	3820	3790
*RE for time of visit	4015	3971	4020	3981
*RE for adolescent id and time of visit (2-level nested model)	3823	3787	3820	3788
*RE for school id, adolescent id, time of visit (3-level nested model)	3811	3777	3819	3788
LPML				
No RE	-2006	-1985	-2009	-1990
RE for adolescent id	-1934	-1916	-1933	-1919
*RE for school type	-1998	-1985	-2003	-1990
*RE for school id	-2002	-1985	-2006	-1990
*RE for adolescent id and school id	-1922	-1906	-1923	-1909
*RE for time of visit	-2007	-1985	-2010	-1990
*RE for adolescent id and time of visit (2-level nested model)	-1924	-1906	-1925	-1909
*RE for school id, adolescent id, time of visit (3-level nested model)	-1920	-1904	-1924	-1909

Table B.7. Results of the Moran's I test to test for spatial autocorrelation in our longitudinal models.

I tested for spatial autocorrelation in my fully adjusted longitudinal models with (a) executive function (EF) score, (b) Strengths and Difficulties Questionnaire (SDQ) total difficulties score and (c) KIDSCREEN-10 Questionnaire Health-Related Quality of Life (HRQoL) score. Fully adjusted models were adjusted for all factors which includes age, area-level deprivation, ethnicity, gender, parental occupation and school type, and in the case of the EF score additionally adjusted for air pollution. Fully adjusted models included a random effect term for adolescent identifier to allow for between-adolescent variance, while I used a random effect term for tests at the time of visit (two levels: first or second visit) for each adolescent to introduce correlation among the repeated measurements If the p-value was statistically significant (< 0.05), it indicated that the data is more spatially clustered than would be expected if spatial processes were random. If the p-value was not statistically significant (> 0.05), it indicated that the spatial distribution of the data is the result of random spatial processes. P-value significance was indicated with an asterisk (*).

	Moran I test statistic	P-value
a	0.002	0.052
b	0.001	0.135
c	0.0009	0.351

Table B.8. Comparison of fully adjusted models with the executive function (EF) score and urban ecosystem type daily exposure rate (DER) based on daytime (12 hrs) or full day (24 hrs) weighting.

I applied a different weighting on the proportionate presence of each urban ecosystem type DER based on daytime (12 hrs) and a full day (24 hrs). I fully adjusted all models for age, air pollution, area-level deprivation, ethnicity, gender, parental occupation and school type. Model I (M I) contained natural space DER, Model II (M II) contained green and blue space DER and Model III (M III) contained grassland and woodland DER. Significance was indicated with an asterisk (*) and can be deduced when the 95% credible interval (CI) excluded zero for these models. Qn1, Qn2, Qn3, Qn4 and Qn5 represented the first, second, third, fourth and fifth quintiles of the Carstairs deprivation index, respectively; occ=occupations; emp=employers.

	Daytime weighting (12 hrs)			Full day weighting (24 hrs)		
	M I: Posterior mean (95% CI)	M II: Posterior mean (95% CI)	M III: Posterior mean (95% CI)	M I: Posterior mean (95% CI)	MII: Posterior mean (95% CI)	M III: Posterior mean (95% CI)
α (intercept)	0.33 (0.27, 0.39)*	0.35 (0.29, 0.41)*	0.31 (0.25, 0.37)*	0.27 (0.21, 0.33)*	0.29 (0.23, 0.35)*	0.25 (0.19, 0.31)*
Natural space DER	0.03 (0.006, 0.06)*	-	-	0.02 (-0.001, 0.04)	-	-
Green space DER	-	0.03 (0.01, 0.06)*	-	-	0.02 (0.01, 0.04)*	-
Blue space DER						
Level 1 (ref)	-	0 (ref)	-	-	0 (ref)	-
Level 2	-	-0.03 (-0.08, 0.02)	-	-	-0.04 (-0.10, 0.01)	-
Level 3	-	-0.04 (-0.09, 0.01)	-	-	-0.02 (-0.07, 0.01)	-
Grassland DER	-	-	-0.01 (-0.03, 0.02)	-	-	0.01 (-0.02, 0.02)
Woodland DER	-	-	0.06 (0.03, 0.08)*	-	-	0.04 (0.02, 0.06)*
Parental occupation						
Managerial/professional occ.	0 (ref)	0 (ref)	0 (ref)	0 (ref)	0 (ref)	0 (ref)
Intermediate occ.	0.01 (-0.04, 0.06)	0.01 (-0.04, 0.06)	0.01 (-0.04, 0.06)	0.03 (-0.02, 0.08)	0.02 (-0.02, 0.08)	0.03 (-0.02, 0.08)
Small emp./own-account workers	-0.01 (-0.05, 0.03)	-0.01 (-0.05, 0.03)	-0.01 (-0.05, 0.04)	-0.01 (-0.06, 0.03)	-0.01 (-0.05, 0.03)	-0.01 (-0.05, 0.03)
Lower supervisory/technical occ.	-0.09 (-0.16, -0.01)*	-0.09 (-0.10, -0.01)*	-0.08 (-0.16, -0.01)*	-0.07 (-0.15, -0.01)*	-0.07 (-0.15, -0.01)*	-0.07 (-0.15, -0.01)*
Semi-routine/routine occ.	-0.03 (-0.08, 0.02)	-0.03 (-0.08, 0.02)	-0.02 (-0.08, 0.02)	-0.01 (-0.05, 0.04)	-0.01 (-0.05, 0.04)	-0.01 (-0.05, 0.04)
Area-level deprivation						
Least deprived (Qn1)	0 (ref)	0 (ref)	0 (ref)	0 (ref)	0 (ref)	0 (ref)
Qn2	0.05 (-0.01, 0.11)	0.05 (-0.01, 0.11)	0.04 (-0.01, 0.11)	0.04 (-0.01, 0.10)	0.04 (-0.01, 0.10)	0.04 (-0.02, 0.10)
Qn3	0.03 (-0.03, 0.09)	0.03 (-0.03, 0.09)	0.02 (-0.04, 0.08)	0.01 (-0.05, 0.08)	0.01 (-0.04, 0.08)	0.01 (-0.05, 0.08)
Qn4	-0.01 (-0.07, 0.05)	-0.01 (-0.07, 0.05)	-0.01 (-0.07, 0.05)	-0.02 (-0.09, 0.04)	-0.02 (-0.09, 0.04)	-0.02 (-0.09, 0.04)
Most deprived (Qn5)	-0.03 (-0.10, 0.04)	-0.02 (-0.10, 0.04)	-0.02 (-0.09, 0.04)	-0.04 (-0.12, 0.02)	-0.04 (-0.11, 0.02)	-0.03 (-0.10, 0.03)

Gender						
Male	0 (ref)	0 (ref)	0 (ref)	0 (ref)	0 (ref)	0 (ref)
Female	0.15 (0.11, 0.19)*	0.15 (0.11, 0.19)*	0.16 (0.12, 0.19)*	0.14 (0.11, 0.18)*	0.14 (0.10, 0.18)*	0.15 (0.11, 0.19)*
Age	0.02 (0.01, 0.04)*	0.02 (0.01, 0.04)*	0.02 (0.01, 0.04)*	0.02 (0.01, 0.04)*	0.02 (0.01, 0.04)*	0.02 (0.01, 0.04)*
NO_2 DER	0.03 (0.01, 0.06)*	0.03 (0.01, 0.06)*	0.01 (-0.01, 0.04)	0.005 (0.004, 0.01)*	0.005 (0.004, 0.01)*	0.005 (0.004, 0.01)*
Ethnicity						
White	0 (ref)	0 (ref)	0 (ref)	0 (ref)	0 (ref)	0 (ref)
Black	-0.15 (-0.21, -0.09)*	-0.15 (-0.21, -0.09)*	-0.15 (-0.21, -0.09)*	-0.15 (-0.21, -0.09)*	-0.15 (-0.21, -0.09)*	-0.15 (-0.21, -0.09)*
Asian	0.07 (0.02, 0.12)*	0.06 (0.02, 0.11)*	0.06 (0.01, 0.11)*	0.06 (0.02, 0.11)*	0.06 (0.01, 0.11)*	0.06 (0.01, 0.11)*
Mixed	0.01 (-0.04, 0.08)	0.01 (-0.04, 0.08)	0.01 (-0.05, 0.07)	0.01 (-0.04, 0.08)	0.01 (-0.04, 0.08)	0.01 (-0.05, 0.07)
Other	-0.12 (-0.32, 0.08)	-0.12 (-0.32, 0.08)	-0.11 (-0.31, 0.08)	-0.11 (-0.32, 0.08)	-0.11 (-0.32, 0.08)	-0.12 (-0.32, 0.08)
School type						
Independent	0 (ref)	0 (ref)	0 (ref)	0 (ref)	0 (ref)	0 (ref)
State	-0.32 (-0.38, -0.27)*	-0.33 (-0.38, -0.28)*	-0.30 (-0.35, -0.25)*	-0.35 (-0.40, -0.30)*	-0.36 (-0.41, -0.31)*	-0.32 (-0.38, -0.27)*

Table B.9. Comparison of fully adjusted models with Strengths and Difficulties Questionnaire (SDQ) total difficulties score (TDS) and urban ecosystem type daily exposure rate (DER) based on daytime (12 hrs) or full day (24 hrs) weighting.

I applied a different weighting on the proportionate presence of each urban ecosystem type DER based on daytime (12 hrs) and a full day (24 hrs). I fully adjusted all models for age, area-level deprivation, ethnicity, gender, parental occupation and school type. Model I (M I) contained natural space DER, Model II (M II) contained green and blue space DER and Model III (M III) contained grassland and woodland DER. Significance was indicated with an asterisk (*) and can be deduced when the 95% credible interval (CI) excluded one for these models. Qn1, Qn2, Qn3, Qn4 and Qn5 represented the first, second, third, fourth and fifth quintiles of the Carstairs deprivation index, respectively; occ=occupations; emp=employers.

	Daytime weighting (12 hrs)			Full day weighting (24 hrs)		
	M I: Posterior mean (95% CI)	M II: Posterior mean (95% CI)	M III: Posterior mean (95% CI)	M I: Posterior mean (95% CI)	M II: Posterior mean (95% CI)	M III: Posterior mean (95% CI)
α (intercept)	8.44 (8.01, 8.87)*	8.33 (7.89, 8.79)*	8.51 (8.09, 8.95)*	8.48 (8.04, 8.94)*	8.38 (7.92, 8.85)*	8.54 (8.10, 9)*
Natural space DER	0.98 (0.96, 1.01)	-	-	0.98 (0.96, 1.01)	-	-
Green space DER	-	0.98 (0.96, 1.01)	-	-	0.98 (0.96, 1.01)	-
Blue space DER						
Level 1 (ref)	-	1 (ref)	-	-	1 (ref)	-
Level 2	-	1.03 (0.98, 1.08)	-	-	1.01 (0.96, 1.06)	-
Level 3	-	1.02 (0.97, 1.06)	-	-	1.03 (0.99, 1.07)	-
Grassland DER	-	-	1 (0.98, 1.02)	-	-	0.99 (0.97, 1.01)
Woodland DER	-	-	0.97 (0.95, 0.99)*	-	-	0.97 (0.95, 0.99)*
Parental occupation						
Managerial/professional occ.	1 (ref)	1 (ref)	1 (ref)	1 (ref)	1 (ref)	1 (ref)
Intermediate occ.	0.93 (0.89, 0.98)*	0.93 (0.89, 0.98)*	0.93 (0.88, 0.98)*	0.93 (0.89, 0.98)	0.93 (0.89, 0.98)*	0.93 (0.88, 0.98)*
Small emp./own-account workers	0.99 (0.95, 1.03)	0.99 (0.95, 1.03)	0.99 (0.95, 1.03)	0.99 (0.95, 1.03)	0.99 (0.95, 1.03)	0.99 (0.95, 1.03)
Lower supervisory/technical occ.	1 (0.93, 1.07)	1 (0.93, 1.07)	0.99 (0.92, 1.06)	1.01 (0.93, 1.07)	1.01 (0.93, 1.07)	0.99 (0.93, 1.07)
Semi-routine/routine occ.	0.98 (0.93, 1.02)	0.98 (0.93, 1.02)	0.97 (0.93, 1.02)	0.98 (0.93, 1.03)	0.98 (0.93, 1.02)	0.98 (0.93, 1.02)
Area-level deprivation						
Least deprived (Qn1)	1 (ref)	1 (ref)	1 (ref)	1 (ref)	1 (ref)	1 (ref)
Qn2	0.99 (0.94, 1.05)	0.99 (0.94, 1.05)	1.01 (0.94, 1.06)	0.99 (0.93, 1.05)	0.99 (0.94, 1.05)	0.99 (0.94, 1.05)
Qn3	1.03 (0.97, 1.09)	1.02 (0.96, 1.09)	1.03 (0.97, 1.09)	1.02 (0.96, 1.08)	1.02 (0.96, 1.08)	1.02 (0.96, 1.09)
Qn4	1.02 (0.96, 1.08)	1.02 (0.95, 1.08)	1.02 (0.96, 1.08)	1.01 (0.95, 1.08)	1.01 (0.95, 1.08)	1.01 (0.95, 1.08)
Most deprived (Qn5)	1.01 (0.94, 1.07)	1.01 (0.94, 1.07)	1.01 (0.94, 1.07)	1.01 (0.93, 1.07)	1.01 (0.93, 1.07)	1.01 (0.93, 1.07)

Gender						
Male	1 (ref)	1 (ref)	1 (ref)	1 (ref)	1 (ref)	1 (ref)
Female	1.05 (1.02, 1.09)*	1.05 (1.02, 1.09)*	1.05 (1.02, 1.09)*	1.05 (1.02, 1.09)*	1.05 (1.02, 1.09)*	1.05 (1.02, 1.09)*
Age	1.01 (0.99, 1.02)	1.01 (0.99, 1.02)	1.01 (0.99, 1.02)	1.01 (0.99, 1.02)	1.01 (0.99, 1.02)*	1.01 (0.99, 1.02)
Ethnicity						
White	1 (ref)	1 (ref)	1 (ref)	1 (ref)	1 (ref)	1 (ref)
Black	1.02 (0.97, 1.08)	1.02 (0.97, 1.08)	1.02 (0.97, 1.08)	1.02 (0.97, 1.08)	1.02 (0.97, 1.08)	1.02 (0.97, 1.08)
Asian	0.91 (0.87, 0.95)*	0.91 (0.87, 0.95)*	0.91 (0.88, 0.96)*	0.91 (0.87, 0.95)*	0.91 (0.87, 0.95)*	0.91 (0.87, 0.95)*
Mixed	1.02 (0.97, 1.08)	1.02 (0.97, 1.08)	1.03 (0.97, 1.09)	1.02 (0.97, 1.08)	1.02 (0.97, 1.08)	1.03 (0.97, 1.09)
Other	1.14 (0.96, 1.35)	1.14 (0.96, 1.35)	1.14 (0.96, 1.35)	1.14 (0.96, 1.35)	1.14 (0.96, 1.35)	1.14 (0.96, 1.35)
School type						
Independent	1 (ref)	1 (ref)	1 (ref)	1 (ref)	1 (ref)	1 (ref)
State	1.10 (1.05, 1.15)*	1.11 (1.06, 1.16)*	1.09 (1.04, 1.14)*	1.10 (1.05, 1.15)*	1.10 (1.05, 1.15)*	1.09 (1.04, 1.14)*

Table B.10. Comparison of fully adjusted models with KIDSCREEN-10 Questionnaire Health-Related Quality of Life (HRQoL) score and urban ecosystem type daily exposure rate (DER) based on daytime (12 hrs) or full day (24 hrs) weighting.

I applied a different weighting on the proportionate presence of each urban ecosystem type DER based on daytime (12 hrs) and a full day (24 hrs). I fully adjusted all models for age, area-level deprivation, ethnicity, gender, parental occupation and school type. Model I (M I) contained natural space DER, Model II (M II) contained green and blue space DER and Model III (M III) contained grassland and woodland DER. Significance was indicated with an asterisk (*) and can be deduced when the 95% credible interval (CI) excluded one for these models. Qn1, Qn2, Qn3, Qn4 and Qn5 represented the first, second, third, fourth and fifth quintiles of the Carstairs deprivation index, respectively; occ=occupations; emp=employers.

	Daytime weighting (12 hrs)			Full day weighting (24 hrs)		
	M I: Posterior mean (95% CI)	M II: Posterior mean (95% CI)	M III: Posterior mean (95% CI)	M I: Posterior mean (95% CI)	M II: Posterior mean (95% CI)	M III: Posterior mean (95% CI)
α (intercept)	0.02 (0.01, 0.04)*	0.02 (0.01, 0.04)*	0.02 (0.01, 0.03)*	0.03 (0.01, 0.04)*	0.02 (0.01, 0.04)*	0.02 (0.01, 0.03)*
Natural space DER	0.93 (0.83, 1.04)	-	-	0.93 (0.83, 1.05)	-	-
Green space DER	-	0.92 (0.82, 1.03)	-	-	0.93 (0.82, 1.04)	-
Blue space DER						
Level 1 (ref)	-	1 (ref)	-	-	1 (ref)	-
Level 2	-	1.11 (0.82, 1.46)	-	-	1.11 (0.83, 1.44)	-
Level 3	-	0.98 (0.76, 1.24)	-	-	0.98 (0.74, 1.25)	-
Grassland DER	-	-	0.88 (0.78, 0.99)*	-	-	0.88 (0.78, 0.99)*
Woodland DER	-	-	1.08 (0.95, 1.21)	-	-	1.10 (0.97, 1.24)
Parental occupation						
Managerial/professional occ.	1 (ref)	1 (ref)	1 (ref)	1 (ref)	1 (ref)	1 (ref)
Intermediate occ.	0.83 (0.56, 1.17)	0.83 (0.56, 1.17)	0.84 (0.56, 1.18)	0.83 (0.56, 1.17)	0.83 (0.56, 1.17)	0.84 (0.56, 1.18)
Small emp./own-account workers	0.99 (0.75, 1.29)	0.99 (0.75, 1.29)	1.01 (0.75, 1.30)	1.01 (0.75, 1.29)	1.01 (0.75, 1.29)	1.01 (0.76, 1.31)
Lower supervisory/technical occ.	1.42 (0.90, 2.10)	1.43 (0.90, 2.11)	1.44 (0.91, 2.13)	1.43 (0.90, 2.11)	1.43 (0.90, 2.11)	1.44 (0.91, 2.13)
Semi-routine/routine occ.	0.95 (0.67, 1.30)	0.95 (0.67, 1.30)	0.96 (0.68, 1.31)	0.96 (0.68, 1.30)	0.96 (0.67, 1.30)	0.97 (0.68, 1.32)
Area-level deprivation						
Least deprived (Qn1)	1 (ref)	1 (ref)	1 (ref)	1 (ref)	1 (ref)	1 (ref)
Qn2	1.17 (0.80, 1.65)	1.16 (0.80, 1.64)	1.16 (0.80, 1.63)	1.16 (0.80, 1.64)	1.15 (0.79, 1.63)	1.16 (0.80, 1.63)
Qn3	0.99 (0.67, 1.41)	0.98 (0.66, 1.40)	0.98 (0.66, 1.39)	0.98 (0.66, 1.41)	0.97 (0.65, 1.39)	0.99 (0.67, 1.41)
Qn4	0.91 (0.61, 1.31)	0.90 (0.60, 1.30)	0.91 (0.61, 1.31)	0.91 (0.60, 1.31)	0.90 (0.59, 1.30)	0.93 (0.62, 1.33)

Most deprived (Qn5)	1.06 (0.69, 1.55)	1.04 (0.69, 1.53)	1.06 (0.70, 1.55)	1.06 (0.69, 1.56)	1.05 (0.68, 1.54)	1.10 (0.72, 1.61)
Gender						
Male	1 (ref)	1 (ref)	1 (ref)	1 (ref)	1 (ref)	1 (ref)
Female	1.95 (1.59, 2.38)*	1.96 (1.59, 2.39)*	1.98 (1.61, 2.42)*	1.95 (1.59, 2.38)*	1.95 (1.59, 2.39)*	1.97 (1.60 ,2.40)*
Age	1.09 (0.99, 1.20)	1.09 (0.99, 1.20)	1.08 (0.98, 1.19)	1.10 (1, 1.20)*	1.10 (1, 1.21)*	1.09 (0.99, 1.19)
Ethnicity						
White	1 (ref)	1 (ref)	1 (ref)	1 (ref)	1 (ref)	1 (ref)
Black	1.68 (1.24, 2.21)*	1.67 (1.24, 2.21)*	1.68 (1.24, 2.21)*	1.68 (1.24, 2.21)*	1.67 (1.24, 2.20)*	1.68 (1.24, 2.22)*
Asian	0.88 (0.67, 1.13)	0.88 (0.67, 1.13)	0.86 (0.66, 1.10)	0.88 (0.67, 1.13)	0.88 (0.67, 1.13)	0.87 (0.66, 1.11)
Mixed	1.81 (1.33, 2.40)*	1.81 (1.33, 2.40)*	1.78 (1.31, 2.36)*	1.81 (1.33, 2.40)*	1.81 (1.33, 2.39)*	1.78 (1.31, 2.35)*
Other	2.63 (1.06, 5.23)*	2.65 (1.07, 5.27)*	2.63 (1.07, 5.23)*	2.62 (1.06, 5.20)*	2.64 (1.06, 5.26)*	2.63 (1.06, 5.23)*
School type						
Independent	1 (ref)	1 (ref)	1 (ref)	1 (ref)	1 (ref)	1 (ref)
State	1.57 (1.19, 2.04)*	1.60 (1.21, 2.09)*	1.71 (1.28, 2.24)*	1.56 (1.18, 2.03)*	1.60 (1.20, 2.09)*	1.69 (1.27, 2.22)*

Table B.11. Contribution of demographic, environmental and socio-economic factor groups based on the difference in pseudo R-squared between the full fixed-effects only Model I (M I) and M I excluding each factor group.

The full fixed-effect only M I included environmental (i.e. natural space daily exposure rate [DER] and air pollution), demographic (i.e. gender, age and ethnicity) and socio-economic variables (parental occupation, area-level deprivation and school type). Mean pseudo R-squared was calculated by dividing the mean squared error between predicted and observed values by the variance of the observed values for each fold in a 10-fold cross validation. Standard error (SE) of the mean pseudo R-squared was calculated by dividing the standard deviation by the square root of the number of measurements. We did not calculate a pseudo R-squared for the Health-Related Quality of Life score because the observed value is binomial, making it impossible to measure a pseudo R-squared.

	Pseudo R-squared	Difference
Executive function score	Mean (SE)	
Full fixed-effects only model	0.104 (0.005)	-
- Environmental variables	0.102 (0.004)	0.002
- Demographic variables	0.084 (0.006)	0.02
- Socioeconomic variables	0.046 (0.003)	0.058
SDQ total difficulties score		
Full fixed-effects only model	0.029 (0.005)	-
- Environmental variables	0.028 (0.002)	0.001
- Demographic variables	0.009 (0.002)	0.02
- Socioeconomic variables	0.021 (0.001)	0.008

Source paper references:

Blangiardo, M., Pirani, M., Kanapka, L., Hansell, A., Fuller, G., 2019. A hierarchical modelling approach to assess multi pollutant effects in time-series studies. PLoS One 14, e0212565.

Simpson, D., Rue, H., Martins, T.G., Riebler, A., Sørbye, S.H., 2017. Penalising model component complexity: A principled, practical approach to constructing priors. Stat. Sci. 32, 1–28.

Appendix C

Published preprint at *UCL Open: Environment*

The work presented in Chapter 4 was informed by a pilot study of the Master student Emily Northridge which I co-supervised, and was submitted for publication at the journal *UCL Open: Environment* where it is currently published as a preprint (Northridge et al., 2020).

Article title: Publicly available data sources to compile an urban natural capital account according to the SEEA EEA: A London case study
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Publicly available data sources to compile an urban natural capital account according to the SEEA EEA: A London case study

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ABSTRACT

Government organisations and other public sector bodies are compiling standardised environmental accounts to encourage more sustainable land use choices and improve management of the natural environment and associated benefits. While the United Nations System of Environmental-Economic Accounting Experimental Ecosystem accounting (SEEA EEA) provides such as framework, practical challenges remain in particular decision-making contexts. In urban areas, natural ecosystems have unique challenges because of anthropogenic pressures, providing a mix of ecosystem services (ES) that may be valued differently compared to non-urban natural ecosystems due to people's proximity to these. It is unknown whether existing publicly available data sources for urban areas are compatible with the SEEA EEA framework and if these sources are sufficient for the development of an inclusive natural capital accounts. Here, we explore whether an inclusive urban natural capital account that includes a broad range of ES can be compiled from publicly available data sources for Greater London between 2007 and 2018. We showed that it was not possible to compile an inclusive urban natural capital account for London per year consistent with the SEEA EEA framework because of issues with (1) temporal inconsistencies, (2) land cover classifications and (3) lack of public access to certain data sources. Greater collaboration between institutions and other organisations could support our understanding of linkages between ecosystem extent, condition and ES flows. Overall, our findings suggest the need for renewed efforts to develop a cohesive source of publicly available data, which could be supported by making interdisciplinary work standard practise.

Keywords: Natural capital, environmental accounting, ecosystem accounting, ecosystem services, urban, London, United Kingdom, SEEA, SEEA EEA

1 INTRODUCTION

Natural capital describes those parts of the natural environment that are capable of contributing to human health and well-being (Natural Capital Committee [NCC], 2013). The benefits that flow from natural capital assets are known as ecosystem services (ES) and are classified into three distinct categories, i.e. (1) provisioning services which include all physical products that we take from the environment, (2) regulating services which maintain environmental processes and sustain the biophysical environment, and (3) cultural services which are the non-material amenities that people gain from interacting with ecosystems (Haines-Young and Potschin, 2018). Some sources recognise a fourth ES category, i.e. supporting services which are defined as the services that maintain earth's conditions so that all other ES can flow (Millenium Ecosystem Assessment [MEA], 2005). Degradation of nature—on which society and the economy as a whole depends upon—in favour of land uses which produce marketable goods has resulting in a 60% decline in ES productivity compared to 50 years ago (MEA, 2005). Identifying the value that natural capital gives to a country is crucial to understand its contributions to human health and well-being and preventing further losses (Stiglitz et al., 2010).

Global commitments are being made by decision-makers to include the value of natural capital into (inter)national accounting practices and GDP calculations—for example, United Nations (UN) Sustainable Develop Goal Targets 15.9 and 17.19 and Aichi Biodiversity Target 2 (CBD, 2010; UN, 2015). The European Union's Biodiversity Strategy posits to 'integrate ecosystems and their services into national and EU accounting and reporting systems' (EC, 2011), and the United Kingdom's (UK) 25 Year Environment Plan states to use 'natural capital approaches to help encourage better uptake of natural capital reporting, standards and accounting across government and business' (Department for Environment, Food & Rural Affairs [Defra], 2018). On a city level, the Greater London Authority (GLA) made commitments to 'promote a natural capital accounting framework for London' (GLA, 2018). Although institutional commitments have been made to account for natural capital across all levels of governance, accounting for the ES flowing from natural capital in terms of national wealth is so far not globally practised.

The UN collaborated with national statistical offices and a wide range of other organisations to develop a statistical framework for valuing natural resources and land in a way that is compatible with the System of National Accounts (SNA). The System of Environmental-Economic Accounting Central Framework (SEEA CF) is a statistical framework that sets standardised concepts, definitions, classifications and accounting rules to enable countries to produce transnationally comparable statistics on their environmental-economic system (UN, 2014a). However, the contribution of most regulating and cultural ES, as well as certain provisioning ES, are currently unrecognised within the SEEA CF. The System of Environmental-Economic Accounting Experimental Ecosystem Accounting framework (SEEA EEA) presented efforts to account for the complete environmental-economic system (UN, 2014b) and is compatible with the structure of the SEEA CF. It enables decision-makers to better understand the value of their natural capital assets and improve decision-making beyond environmental policies (Vardon et al., 2017). So far, more than 24 countries have compiled SEEA EEA accounts, even though all vary in scope and resolution (Hein et al., 2020). Meanwhile, experts engaged in extensive discussions and testing of concepts to further advance the SEEA EEA, and a revised SEEA EEA is expected to be completed in 2021 (UN, 2020, 2019).

The UK Office for National Statistics (ONS) has worked with Defra, using the SEEA EEA framework, to develop accounts for the value of urban natural capital assets. This has resulted in a growing range of work focusing on understanding the value of urban natural capital in the UK (EFTEC, 2017; ONS, 2019; Vivid Economics, 2017). These urban environmental accounts are useful for understanding the value of urban natural capital. However not all were compiled in a way consistent with the SEEA EEA framework. Here, we explore whether it is possible to (1) compile an urban natural capital account according to the SEEA EEA framework from publicly available data sources for London and (2) use of the SEEA EEA framework to capture the value of individual ecosystem assets at a reasonable spatial granularity in an urban context.

2 METHODS

We identified publicly available data sources relevant to compile an urban natural capital account according to SEEA EEA through reports and studies using the Google Scholar search engine and government open data records. The ecosystem accounting area considered in this analysis is Greater London (UK), which is defined here as the 32 London boroughs and the City of London. We contacted experts and organisations that deal with environmental data sources or have expertise in environmental accounting for input; we specifically contacted Defra, Geofabrik, Greenspace Information for Greater London (GiGL), the Ordnance Survey (OS), Sustain and Thames Water. We only included publicly available data sources if these sources were published between 2007 and 2018. We did not seek to make a definitive statement on the number of publicly available data sources, because there are privately-owned data sources that might be available after usage is granted by the data owner. We also included publicly available data sources with only partial spatial or temporal cover for Greater London and gathered information for each mapped data source, if applicable, on authorship, update frequency, spatial extent, unit or resolution, data format (e.g. raster, vector format), licensing or usage restrictions and historic data availability (ESM Appendix, Table 1 and 2).

2.1 ECOSYSTEM EXTENT

Land cover classifications described in the SEEA CF and SEEA EEA bring about issues when developing an urban natural capital account. For example, the land cover class 'artificial surfaces' is useful when assessing urban areas on a national and international scale; however, this land cover class may not useful when developing a natural capital account on an urban scale because it may exclude smaller green spaces. The land cover classifications from the SEEA CF and SEEA EEA were either (1) too detailed for use as a land cover classification in an urban context or (2) not applicable to the area of Greater London (e.g. mangroves). The SEEA framework aims to be comprehensive, meaning it accounts for all land cover classifications within the ecosystem accounting area. Considering the issues with land cover classifications from the SEEA CF and SEEA EEA in an urban context, we therefore used the land cover classifications from these frameworks to develop a simplified urban land cover classification (Figure 1) (UN, 2014a, 2014b). We excluded the following land cover classes from our analysis: barren land, coastal water bodies, mangroves, permanent snow and glaciers, sea and sparsely vegetated areas. We also added two land cover classes specifically for data sources without identifiable land covers (i.e. unspecified green and blue space) (Figure 1). This is consistent with suggestions from SEEA experts to define urban land cover based on (1) natural and semi-natural land covers which more or less retain natural features and (2) urban green and blue land covers which are embedded in the built-up urban area and are significantly altered or managed to be

classified as a natural or semi-natural land cover (Wang et al., 2019). Finally, we identified all publicly available data sources that provide spatially explicit land covers based on our urban land cover classification per year. We classified data sources which did not specify a year when created in our results as unclassified (U).

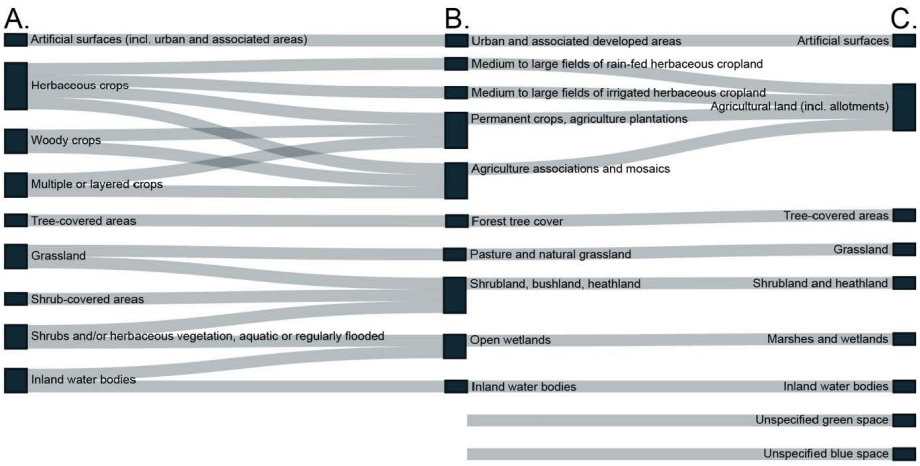

Figure 1. Connecting different land cover classifications. Overview and connections between the (A) land cover classification based on the System of Environmental-Economic Accounting Central Framework (SEEA CF), (B) land cover/ecosystem functional unit classes from the System of Environmental-Economic Accounting Experimental Ecosystem Accounting and (C) our simplified urban land cover classification (UN, 2014a, 2014b). Our urban land cover classification did not include the following land cover classes: barren land, coastal water bodies, mangroves, permanent snow and glaciers, sea and sparsely vegetated areas. We also specified two land cover classes specifically for data sources without identifiable land covers (i.e. unspecified green and blue space).

2.2 ECOSYSTEM CONDITION

Although not the only definition, ecosystem condition is broadly defined as the capacity of ecosystems to provide ES (UN, 2014a, 2014b). We identified data sources relevant to ecosystem condition by assessing which ecosystem condition is applicable per year. We classified data sources which did not specify a year when created in our results as unclassified (U). We included publicly available imagery from satellites because this data type can be used for assessing ecosystem extent and condition. Specific wavelengths of satellite imagery, for example, can be used to calculate vegetation indices such as the Normalised Difference Vegetation Index (NDVI). NDVI is based on the process where healthy vegetation absorbs more light in the photosynthetically active region compared to degraded vegetation or non-vegetated area and is therefore a proxy for measuring ecological extent and condition of unspecified green space (Kriegler et al., 1969). Specifically, it can be used to assess vegetation productivity, and in combination with surface land temperature to develop soil moisture indicators (Han et al., 2010; Pettorelli et al., 2005).

2.3 ECOSYSTEM SERVICE FLOWS

We identified publicly available data sources relevant to estimating ES flow from natural capital assets and what ES class it belonged to (i.e. provisioning, regulating or cultural ES). We based classification of ES flows on the Common International Classification of Ecosystem Services (CICES) (Haines-Young and Potschin, 2018). As we do not seek to make a definitive statement of which ES based on CICES are

relevant to urban natural capital accounts, a single publicly available data source was considered sufficient to indicate the possibility to assess a particular ES flow. Several reports have developed urban natural capital accounts in London and the UK (EFTEC, 2017; ONS, 2019; Vivid Economics, 2017a). However, these reports only focus on a limited number of ES flows and do not include the complete list of ES according to CICES. We simply added those ES for which we found publicly available data sources, but we acknowledge that other ES may be relevant to develop an inclusive urban natural capital account. We also did not explore the potential for modelling and other analytical techniques to provide ES unit values and factors.

2.4 URBAN NATURAL CAPITAL ACCOUNTS FOR LONDON

We developed a matrix linking ecosystem extent and condition with ES flows based on similar approach in a scoping study to develop an urban natural capital account for the whole of the UK (ESM Appendix, Table 3) (EFTEC, 2017). This matrix then formed the basis for assessing the possibility to develop an urban natural capital account for London per year.

3 RESULTS

Our analysis found 66 publicly available data sources relevant to compile an urban natural capital account for London based on the SEEA EEA framework. Of these, 29 data sources were relevant to ecosystem extent, 23 to ecosystem condition and 16 to ES flows.

3.1 ECOSYSTEM EXTENT

Our results showed that it is possible to measure ecosystem extent for all 7 land cover classes per year (Figure 2A). However, the overall number of data sources per land cover class was low. A high number of identified data sources did not specify a particular land cover class and were therefore classified as unspecified green or blue space. In addition, certain data sources seemed useful for determining ecosystem extent at first but are not useful after detailed analysis. For example, the global land cover maps from the European Space Agency (ESA) Climate Change Initiative (CCI) identified all 7 land cover classes for all years between 2007 and 2018 (ESA, 2017). However, the coarse spatial resolution (300 m per pixel) of this data source makes it extremely granular for urban ecosystem accounting in Greater London and a large part of London was classified as urban area. Meanwhile, the Land Cover Map released by the UK Centre for Ecology & Hydrology had a detailed land cover classification, but a poor temporal availability (i.e. a land cover classification for the years 2007 and 2015) (CEH, 2017). We therefore identified several data sources with high-quality spatial resolution but low-quality time series to assess ecosystem extent, while one data source had a high-quality time series but a low-quality spatial resolution (Figure 2B).

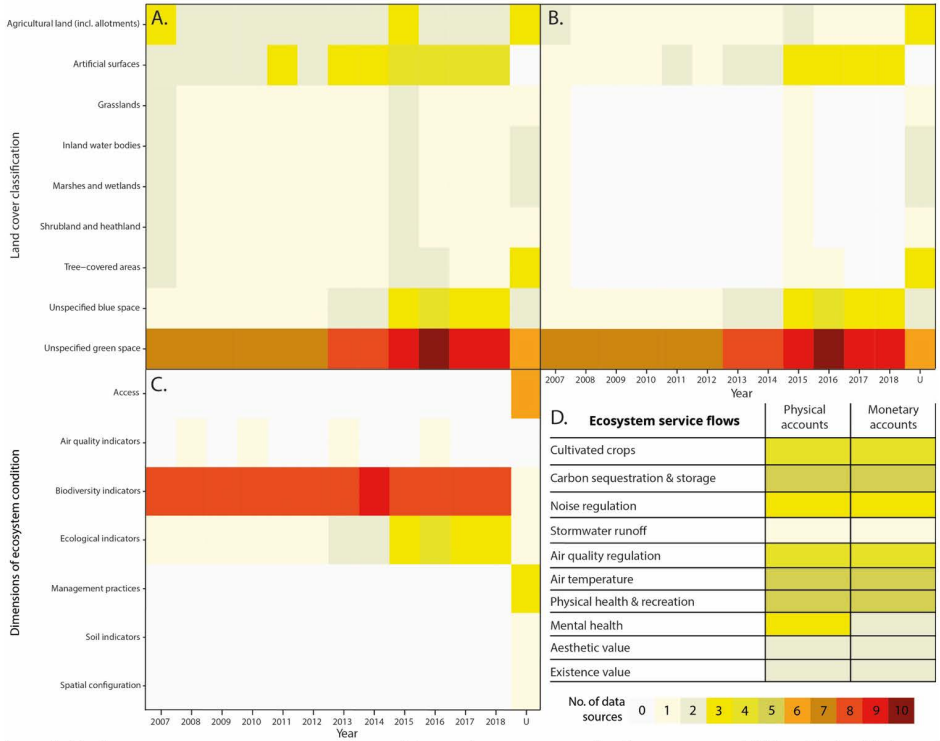

Figure 2. Amount of publicly available data sources on ecosystem extent, condition and ecosystem service flows per year. All identified publicly available data sources for (A) ecosystem extent, (B) ecosystem extent excluding land cover maps from the European Space Agency Climate Change Initiative (ESA, 2017), (C) broad dimensions of ecosystem condition and (D) ecosystem service flows in biophysical and monetary terms. Data sources without an identifiable year were marked as unclassified or 'U'. Data sources without an identifiable urban land cover classification were classified as 'unspecified green space' or 'unspecified blue space'.

3.2 ECOSYSTEM CONDITION

We identified only two broad dimensions of ecosystem condition that can be assessed on a yearly basis based on the identified data sources, i.e. biodiversity indicators and ecological condition (Figure 2C). We also identified that air quality indicators could be assessed for several years (i.e. 2008, 2010, 2013 and 2016) through a single data source called the London Atmospheric Emissions Inventory. All other data sources on ecosystem condition were found to have no identifiable year. However, some experts argue that particular ecosystem extent and conditions indicators may not change that often—particularly in urban areas—suggesting these could be used for multiple years. Some data sources also seemed useful for determining particular indicators of ecosystem condition but were considered less useful after detailed analysis. For example, a large part of the point and polygon species records from GIGL were collected before 2007, and sightings between 2007 and 2018 were often based on observations from volunteers, resulting in varying record counts between London boroughs (GIGL, 2017).

3.3 ECOSYSTEM SERVICE FLOWS

We identified 4, 8 and 9 publicly available data sources relevant to develop provisioning, regulating and cultural ES, respectively (Figure 2D). We found substantially more regulating and cultural ES compared to provisioning ES, which may suggest urban ecosystems are much less important for delivering direct benefits to human health and well-being such as biotic and abiotic goods (e.g. biomass and water), and are more important for delivering indirect benefits to human health and well-being (e.g. noise regulation, air temperature, physical or mental health).

3.4 URBAN NATURAL CAPITAL ACCOUNTS FOR LONDON

By combining all publicly available data sources that identify ecosystem extent, condition and ES flows, we found that it is not possible to develop a physical or monetary natural capital accounts for London for each year between the years 2007 and 2018. However, it was possible to develop a limited urban natural capital account when the year remained unspecified. Although this does not adhere to the strict definition for developing an inclusive natural capital account for London, use of publicly available data on ecosystem extent, ecosystem condition and ES flow with no specified year does enable the development of a limited natural capital account as previous studies have done (EFTEC, 2017; Vivid Economics, 2017a).

4 DISCUSSION

Our results were a first attempt to explore whether the development of an urban natural capital account for London was feasible. Our results showed that it was not possible to compile an inclusive natural capital account for London according to the SEEA EEA framework. We did not find publicly available data for key provisioning, regulating and cultural ES, while we found no data for certain years between 2007 and 2018, indicating that currently only a natural capital account with limited scope and time-coverage was possible. Our paper also highlighted 7 mutually exclusive urban land covers that could be used to create an urban natural capital account for London (excluding unspecified green and blue space). Certain urban land covers are heterogeneous and intensively managed, and therefore these natural or semi-natural land covers might not always be easily categorised into a particular land cover. For example, engineered or designed natural assets such as green roofs and walls can be a mosaic of vegetated and impervious land covers, and are better classified as unspecified green or blue

space as suggested by SEEA experts (Wang et al., 2019). Overall, our results highlighted that a considerable effort is needed to (1) address data gaps on ecosystem extent, condition and ES flows, and (2) improve our understanding of the linkages between ecosystem extent, condition and ES flows as discussed in section 4.1 and 4.2.

4.1 DATA GAPS

Institutions and other organisations need to make a concerted effort to address the data gaps found in this paper. Without addressing these needs, it will remain problematic to develop an urban natural capital account for London according to the SEEA EEA framework. We identified three main reasons for the data gaps related to ecosystem extent and condition, i.e. issues related to (1) temporal inconsistencies, (2) land cover classifications, and (3) lack of public access to certain data sources. Stock take over time, which includes ecosystem extent and condition, is a key component of accounting. Accounts are ideally created based on data sources containing similar sampling approaches at regular time intervals. In our analysis however, 14 out of 29 data sources for ecosystem extent had no identifiable time of sampling, while 2 other data sources from GiGL were sampled before 2007 (i.e. Biodiversity Action Plan habitat data from 1989 and 1995). The remaining data sources for ecosystem extent (i.e. 15 out of 29) were able to cover each land cover annually, but this was dependent on the granular data from the ESA CCI as indicated in Section 3.1 (Figure 2). Some experts argue that ecosystem extent and condition indicators do not change that readily and are burdensome to maintain annually, especially in an urban context. Although this implies a natural capital account would not be fully compliant with the SEEA EEA framework, it does provide a practical solution to a lack of annual data as has been done in previous studies (EFTEC, 2017; Vivid Economics, 2017b).

A number of data sources did not classify urban ecosystems according to a particular land cover, but rather classified spaces based on land uses such as public parks, school grounds or cemeteries. For example, the OS MasterMap Greenspace layer only had one identifiable urban land cover, i.e. agricultural land (incl. allotments), while all other spaces were classified in our analysis as unspecified green space (OS, 2004). Although these data sources were accurate, classification according to land use instead of land cover is not always useful for estimating ecosystem extent. Sometimes land use can infer a particular land cover such as bowling green, which is a close-mown stretch of grassland used for playing particular sports. However, other land uses such as religious grounds or cemetery may have varying land covers such as Abney Park, which is an old forested cemetery, while the old and new Camberwell cemetery consist of well-maintained grasslands. Therefore, land use is not always useful for assessing urban land cover and developing a natural capital account. Certain data sources also require greater detail for use in an urban context. For example, the Land Cover Map from 2007 and 2015 classified pixels according to 21 terrestrial and freshwater habitats outlined by the UK Biodiversity Action Plan (CEH, 2017; Jackson, 2000). However, most of London was classified as a single land cover (i.e. urban land cover), making this data source more useful on a national level but less detailed for identifying smaller areas of natural or semi-natural land cover in London.

Lack of access to certain data sources could address important data gaps for developing a natural capital account for London. For example, the i-Tree Eco London survey was undertaken in 2014 to collect data on single trees and plots of trees in London (Treeconomics London, 2015). The survey

found that London's urban forest comprised of more than 8 million trees and supports valuation of a variety of ecosystem services such a carbon capture and storage, rainwater interception and removal of air pollution (Treeconomics London, 2015). Similarly, private utility companies such as Thames Water and Affinity Water provide Londoners with water and sewerage services, but data on water assets are scarce and often not publicly available. Lack of access to certain data sources makes it difficult for developing an inclusive London's natural capital account. Resolving data privacy issues and making data sources publicly available are a key component for developing an inclusive natural capital account for London according to the SEEA EEA framework.

4.2 LINKAGES BETWEEN ECOSYSTEM EXTENT, CONDITION AND ES FLOWS

Current lack of understanding of the interlinkages between ecosystem extent, condition and ES flows is complicated because these interlinkages are multi-dimensional, multi scale, and non-linear (Mace, 2019). For example, low levels of habitat fragmentation do not necessarily affect pollination services until a tipping-point is reached, after which pollination services reach a alternative stable state (Selkoe et al., 2017). Attempts to connect ecosystem extent and condition to ES flows becomes complicated., suggesting that institutions and other organisations need to cooperate to address these knowledge gaps in the interpretation and use of ecosystem accounts (Maes et al., 2019). This also suggests that communication between institutions and other organisations needs to be facilitated (Maes et al., 2019). For example, both Defra, ONS and GLA are working on the development of urban natural capital accounts. Increased collaboration and sharing practices could enhance overall outcomes for urban natural capital accounting. In 2015, the United Nations Statistical Division (UNSD) in collaboration with the UN Environment Programme, the World Bank and the European Union organised the Forum of Experts in SEEA EEA which was set up to connect stakeholders and share best practices on experimental ecosystem accounting. This Forum seeks to build on existing methods and practices to expand the international framework for environmental-economic accounting. Similarly, Defra in collaboration with different UK research councils organised the Valuing Nature Programme with the aim to fund research and support researchers in making links with policymakers, business and practitioners. It is uncertain however whether sharing platforms such as the Forum of Experts in SEEA EEA or the Valuing Nature Network will bring about improvements in cross-disciplinary communication, research on knowledge gaps, and development of publicly available data sources.

5 CONCLUSIONS

Our findings showed that building an inclusive natural capital account for London was currently not possible with a simplified urban land cover classification based on the SEEA CF and SEEA EEA. A more simplified urban land cover classification was preferred for classifying urban ecosystems and building an urban natural capital account because the land cover classifications from SEEA CF and SEEA EEA were (1) too detailed for practical use in urban areas or (2) simply not applicable to our study area of Greater London. Furthermore, the lack of temporal availability of data sources for all urban land cover classifications further complicates the development of an urban natural capital account for London consistent with SEEA EEA. However, it is argued by some experts that particular ecosystem extent and condition indicators may not change that readily— especially in urban areas —and could be used for multiple years. Based on our findings, we translate the challenges to develop urban natural capital accounts and advance urban research more broadly in two parts:

- Renewed efforts are needed to develop better publicly available data sources. By addressing key gaps such as temporal inconsistencies and lack of public access, more data sources could become available that are publicly accessible and updated annually. This would support researchers and decision-makers in their efforts to develop urban natural capital accounts according to the SEEA EEA framework.
- Publicly available data sources need to be underpinned by a cohesive classification framework, which includes realistic land cover classifications for urban ecosystems. By addressing silo-thinking between academic institutions, decision-makers and the private sector, and making interdisciplinary work standard practice, more cohesive data sources may become available for the development of urban natural capital accounts. This could increase support for including new guidelines in the SEEA EEA guidelines particularly for urban ecosystems, and some of this work is already under way (Wang et al., 2019).

Our paper was framed within the broader discussion on the role of natural capital accounting for urban nature conservation by showing that publicly available data sources were not sufficient to develop an inclusive natural capital accounts for London according to the SEEA EEA framework. Future research could include expanding our analysis for publicly available data sources on ES flows that can be inferred from ES modelling and other techniques, amongst others. The abovementioned steps were suggested to address the challenge of dealing with gaps in the data. Through these steps, researchers and decision-makers are encouraged to contribute to the future management of urban ecosystems and the benefits these can deliver to human health and well-being.

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7 CONFLICTS OF INTEREST

The authors declare no conflicts of interest with this work.

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Table C.1. Classification frameworks and associated ecosystem services relevant for cognitive and mental health benefits received from exposure to urban ecosystems according to (1) the System of Environmental-Economic Accounting Ecosystem Accounting (Table 6.3 in UN, 2021) and (2) the Common International Classification of Ecosystem Services (CICES) (Appendix 1 in Haines-Young and Potschin, 2018).

Classification framework	Ecosystem service		Code
The SEEA EA framework	Cultural services	Recreation-related services	-
		Visual amenity services	-
		Spiritual, symbolic and artistic services	-
CICES V5.1	Cultural services (Biotic)	Characteristics of living systems that enable activities promoting health, recuperation or enjoyment through active or immersive interactions	3.1.1.1
		Characteristics of living systems that enable activities promoting health, recuperation or enjoyment through passive or observational interactions	3.1.1.2
		Characteristics of living systems that are resonant in terms of culture or heritage	3.1.2.3
		Characteristics of living systems that enable aesthetic experiences	3.1.2.4
	Cultural services (Abiotic)	Natural, abiotic characteristics of nature that enable active or passive physical and experiential interactions	6.1.1.1

Table C.2. Classification of the environment according to the National Ecosystem Services Classification System (NESCS).

The NESCS is the national classification for ecosystem services in the United States of America (US EPA, 2015).

Environmental class	Environmental subclass
1. Aquatic	11. Rivers and streams
	12. Wetlands
	13. Lakes and ponds
	14. Near coastal marine
	15. Open ocean and seas
	16. Groundwater
2. Terrestrial	21. Forests
	22. Agroecosystems
	23. Created greenspace
	24. Grasslands
	25. Scrubland/shrubland
	26. Barren/rock and sand
	27. Tundra
	28. Ice and snow
3. Atmospheric	31. Atmospheric

Table C.3. Classification of end-products according to the National Ecosystem Services Classification System (NESCS).

The NESCS is the national classification for ecosystem services in the United States of America (US EPA, 2015). Not all end-products have developed categories for subclass because the end-product class can be decomposed in a variety of ways. End-product subclass examples are available in the original table (Table 4-3 in US EPA, 2015).

End-product class	Definition	End-product subclass
1. Water	Liquid and solid forms of water	11. Snow/ice 12. Liquid water
2. Flora	All plant, fungal and unicellular life	Specific classes/species of flora
3. Fauna	All animal life	Specific classes/species of fauna
4. Other biotic components	All other biota or biotic material that are not part of or attached to a currently living floral or faunal source	Specific types of natural material
5. Atmospheric components	Components of the atmosphere (excluding categories described above)	51. Air 52. Solar light/radiation
6. Soil	The unconsolidated mineral or organic matter on the surface of the Earth	Specific types of soil
7. Other abiotic components	Other abiotic material (cannot be attributed to soil, atmosphere or water)	Specific types of natural material
8. Composite end-products	A composite set of specific elements and components of single or multiple environmental classes	81. Scapes: • views • sounds and scents of land, sea, sky or a combination 82. Regulation of extreme events 83. Presence of environmental class/subclass
9. Other end-products	All other end-products (not elsewhere classified)	

Table C.4. Classification of direct use/non-use according to the National Ecosystem Services Classification System (NESCS).

The NESCS is the national classification for ecosystem services in the United States of America (US EPA, 2015). Detailed definitions of each direct use/non-use are available on the original table (Table 4-6 in US EPA, 2015).

Direct use/non-use class	Direct use/non-use subclass	Direct use/non-use detail
1. Direct use	11. Extractive use	1101. Raw material for transformation 1102. Fuel/energy 1103. Industrial processing 1104. Distribution to other users 1105. Support of plant or animal cultivation 1106. Support of human health and life or subsistence 1107. Recreation/tourism 1108. Cultural/spiritual activities 1109. Information, science, education, and research 1199. Other extractive use
	12. In-situ use	1201. Energy 1202. Transportation medium 1203. Support of plant or animal cultivation 1204. Waste disposal/assimilation 1205. Protection or support of human health and life 1206. Protection of human property 1207. Recreation/tourism 1208. Cultural/spiritual activities 1209. Aesthetic appreciation 1210. Information, science, education, and research
2. Non-use	21. Existence	2101. Existence
	22. Bequest	2102. Bequest
	23. Other non-use	2103. Other non-use

Table C.5. Classification of Direct Users according to the National Ecosystem Services Classification System (NESCS).

The NESCS is the national classification for ecosystem services in the United States of America (Table 4-7. in US EPA, 2015).

Direct user class	Direct user subclass
1. Industry	111. Agriculture, forestry, fishing and hunting
	121. Mining
	122. Utilities
	123. Construction
	131-33. Manufacturing
	142. Wholesale trade
	144-45. Retail trade
	148-49. Transportation and warehousing
	151. Information
	152. Finance and insurance
	153. Real estate rental and leasing
	154. Professional, scientific, and technical services
	155. Management of companies and enterprises
	156. Administrative and support and waste management and remediation services
	161. Education services
	162. Health care and social assistance
	171. Arts, entertainment, and recreation
	172. Accommodation and food services
	181. Other services (except public administration)
2 Households	201. Households
3. Government	301. Government

Source paper references:

Haines-Young, R., Potschin, M., 2018. Common International Classification of Ecosystem Services (CICES) V5.1. Nottingham.

UN, 2021. System of Environmental-Economic Accounting—Ecosystem Accounting: Final Draft. New York.

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Report developed in consultation with Defra

This report was developed during a secondment at the Environment Analysis Unit at Defra in July 2018 and formed the basis for my publication in the journal *Ecosystem Services* in August 2020.

Accounting for natural capital benefits in public sector decision-making

Draft paper for consultation prepared by University College London Institute for Sustainable Resources with support from the Defra Environment Analysis Unit.

*The term **natural capital** is increasingly used to describe the parts of the environment that provide benefits to people. Natural capital underpins all other types of capital — manufactured, human, social — and is the foundation on which our economy, society and prosperity are built. Key benefits provided by natural capital include clean air and water, food, energy, wildlife, recreation, and protection from hazards.(1)*

*The UK Government has made several national and international commitments to account for natural capital benefits and risks in public sector decision-making. This paper is intended to inform efforts to implement these commitments. It presents a preliminary assessment of how **(1)** the condition of natural capital assets is affected by decision-making across different public sector institutions, and **(2)** accounting and assessment of natural capital could support selected non-environmental public policy objectives. Illustrative case studies are presented for the policy domains of transport and health. Key messages are highlighted in Figure 1.*

UK Government commitments concerning natural capital

At an international level, the UK has committed to implement the 2030 Agenda for Sustainable Development,(2) including 17 Sustainable Development Goals and 169 associated Targets. The 2030 Agenda explicitly recognises that 'social and economic development depends on the sustainable management of our planet's natural resources'. Two Targets are specifically focused on accounting for natural capital: Target 15.9 calls for the integration by 2020 of 'ecosystem and biodiversity values into national and local planning, development processes, poverty reduction strategies and accounts.' Target 17.19 calls for the development by 2030 of 'measurements of progress on sustainable development that complement gross domestic product, and support for statistical capacity building in developing countries.'

At a national level, the current government's 2017 manifesto pledged to 'be the first generation to leave the environment in a better state than we inherited it' and produce a comprehensive 25 Year Environment Plan.(3) The 25 Year Plan was released in January 2018 and includes several relevant commitments, for example to:

- Improve and expand the range of tools and guidance that support biodiversity net gain approaches, including through the future incorporation of natural capital measures.
- Use our prominence as innovators to develop new approaches and techniques that take account of natural capital.
- Continue the work with the Office for National Statistics to develop a full set of natural capital accounts for the UK that are widely understood and shared internationally.
- Improve our understanding and valuation of the benefits of natural capital through our own research and working with the research community, learning from best practice abroad where appropriate.
- Better incorporate the full spectrum of natural capital and the value of the benefits it provides into analysis and appraisal across government.

Key messages	Supporting analysis
– 85 public sector institutions perform policy and planning, regulatory, financial, operational, or technical activities that affect natural capital assets.	Summary – Page 2. Methods and detailed results – Annex 1.
– The policy objectives of at least 60 public sector institutions are affected by natural capital goods, services and associated risks. Services with cross-cutting relevance to policy delivery include natural hazard regulation, and support for health or well-being.	Summary – Page 2. Methods and detailed results – Annex 2.
– 30% of reviewed policy objectives published by DfT, and 4% of those published by DHSC, have potential impacts on natural capital. 15% and 10% of reviewed DfT and DHSC policy objectives are affected by natural capital goods, services, and associated risks, respectively.	Refer to Pages 4 to 7 for detailed results.
– UK Government investment in natural capital is not currently accounted for across Ministerial Departments and other bodies. Preliminary analysis for 2015/2016 estimates a direct spend by UK Government of £805 million on natural capital management.	Summary – Page 7. Methods and detailed results in reference.
– Public sector management of the UK's natural capital assets could be enhanced by coordination structures that feature cross-Departmental representation.	See discussion on Page 7.

Figure 1: Key messages and supporting analysis. Detailed methods and results are documented in Annexes 1 and 2.

Current progress of UK Government towards accounting for natural capital

Current progress by the UK Government to implement the commitments summarised on Page 1 includes the following actions:

- Publication of the **new Green Book** in April 2018, including guidance on use of non-market values of natural capital in appraisal and evaluation.[4]
- Establishment in 2012 of the **Natural Capital Committee**, which advises the UK Parliament on management of natural capital. The Committee supported development of the 25 Year Environment Plan and has produced several reports on the state of the UK's natural capital.[5]
- Development and maintenance of annual environmental accounts by the Office for National Statistics and Defra.[6] These are based on, and inform ongoing development of, the UN System for Environmental-Economic Accounting.[7]

Public sector institutions that affect the condition of natural capital

The research team reviewed the websites of all public bodies listed in the 2015 data directory.[8] The review identified a total of 85 public institutions that perform activities affecting the condition (extent and composition) of natural capital assets located in the UK. These 85 institutions are listed in **Figure 2** below and are classified as follows:

- **Geographical jurisdiction** — United Kingdom (UK), England, Scotland, Wales, Northern Ireland and local jurisdictions.

Functional classification of activities:

- **Policy and planning** — the institution identifies and organises activities required to achieve a particular goal, involving the creation and maintenance of policies and plans. For example, the Planning Inspectorate deals with planning appeals, planning applications and other planning-related work for various types of infrastructure.
- **Regulation** — the institution monitors, guides and controls particular public and/or private actors, which can include enforcing government controls and restricting a particular sector. For example, the Civil Aviation Authority regulates UK airline and airport safety standards, and security arrangements at UK airports.
- **Finance** — the institution manages money in such a manner to accomplish the objectives of the organisation. For example, HM Treasury controls public spending (including departmental spending), public sector pay and pensions, annually managed expenditure (AME) and welfare policy, and capital investments.
- **Operations** — the institution brings together material and/or immaterial assets to produce a particular product or service. For example, Network Rail operates and develops Britain's railway, which includes tracks, bridges, crossings and stations to deliver well-functioning railway infrastructure to all its users.
- **Technical** — the institution provides an advisory role to other institutions, including the responsibility to manage and share data and statistics. For example, the UK Expert Committee on Pesticides provides technical advice to the government on the science relating to pesticides.

Non-environmental policy objectives that are affected by natural capital

The research team reviewed selected institutional objectives published by all public bodies listed in the 2015 data directory. These institutional objectives were then classified qualitatively in terms of whether or not their delivery was affected by natural capital goods, services (including ecosystem services) or associated risks. The Common International Classification of Ecosystem Services (Version 5.0) was used as a general reference tyopology for these benefits and risks.[9] For objectives classified as affected by natural capital, the nature of this dependency was summarised in order to identify cross-cutting themes.

The policy objectives of at least 60 institutions were classified as affected by natural capital. As shown in **Figure 3** below, these affects can be classified into three broad themes, where natural capital management: **(1)** is a core objective of the relevant institution, **(2)** affects institutional objectives by regulating natural hazards (e.g. flooding, air quality, climate change), and **(3)** provides goods and services that support health and well-being (e.g. space for recreation).

Natural hazards regulation was the most prevalent cross-cutting benefit of natural capital, being relevant to the policy objectives of 46/60 (76%) relevant public institutions. The policy objectives of 24/60 (40%) relevant institutions were classified as affected by natural capital goods and services that support health and well-being.

Figure 2: (BELOW) List of UK public sector institutions that perform activities affecting the condition of natural capital assets. Refer to Annex 1 for detailed results and methods.

Policy and planning function

United Kingdom
- Department for Business, energy and Industrial Strategy (BEIS)
- Department for Digital, Culture, Media & Sport (DCMS)
- Department for Education
- Department for Environment, Food and Rural Affairs (Defra)
- Department for Transport (DfT)
- Department of Health and Social Care (DHSC)
- HM Treasury
- Ministry of Defence (MoD)
- Ministry of Housing, Communities and Local Government

England
- Environment Agency
- Homes England
- Marine Management Organisation
- Planning Inspectorate

Scotland
- Agriculture and Rural Economy Directorate
- Economic Development Directorate
- Housing and Social Justice Directorate
- Energy and Climate Change Directorate
- Environment and Forest Directorate
- Health Finance Directorate
- Learning Directorate
- Marine Scotland Directorate

Wales
- Economy, Skills and Natural Resources Group
- Education and Public Services Group
- Health and Social Services Group
- Planning Inspectorate

Northern Ireland
- Department for Infrastructure
- Department of Agriculture, Environment and Rural Affairs, incl. Northern Ireland Environment Agency
- Department of Communities
- Department for the Economy
- Department of Education
- Department of Health

Local authorities

Legend:

United Kingdom	Scotland
England	Wales
Northern Ireland	Local

Regulatory function

United Kingdom
- Civil Aviation Authority
- Department for Business, energy and Industrial Strategy (BEIS)
- Department for Digital, Culture, Media & Sport (DCMS)
- Department for Education
- Department for Environment, Food and Rural Affairs (Defra)
- Department for Transport (DfT)
- Department of Health and Social Care (DHSC)
- HM Treasury
- Ministry of Defence (MoD)
- Ministry of Housing, Communities and Local Government
- Office of Gas and Electricity Markets
- Office of Rail and Road (ORR)
- Oil and Gas Authority (OGA)

England
- Environment Agency
- Marine Management Organisation
- The Water Services Regulation Authority

Scotland
- Agriculture and Rural Economy Directorate
- Economic Development Directorate
- Housing and Social Justice Directorate
- Energy and Climate Change Directorate
- Environment and Forest Directorate
- Financial Strategy Directorate
- Health Finance Directorate
- Learning Directorate
- Marine Scotland Directorate

Wales
- Economy, Skills and Natural Resources Group
- Education and Public Services Group
- Health and Social Services Group
- Natural Resources Wales
- The Water Services Regulation Authority

Northern Ireland
- Department for Infrastructure
- Department of Agriculture, Environment and Rural Affairs, incl. Northern Ireland Environment Agency
- Department of Communities
- Department for the Economy
- Department of Education
- Department of Finance
- Department of Health

Local authorities

Financial function

United Kingdom
- Department for Business, energy and Industrial Strategy (BEIS)
- Department for Digital, Culture, Media & Sport (DCMS)
- Department for Education
- Department for Environment, Food and Rural Affairs (Defra)
- Department for Transport (DfT)
- Department of Health and Social Care (DHSC)
- HM Treasury
- Ministry of Defence (MoD)
- Ministry of Housing, Communities and Local Government

England
- Environment Agency
- Marine Management Organisation
- Rural Payments Agency

Scotland
- Agriculture and Rural Economy Directorate
- Economic Development Directorate
- Housing and Social Justice Directorate
- Energy and Climate Change Directorate
- Environment and Forest Directorate
- Financial Strategy Directorate
- Health Finance Directorate
- Learning Directorate
- Marine Scotland Directorate

Wales
- Economy, Skills and Natural Resources Group
- Education and Public Services Group
- Health and Social Services Group
- The Water Services Regulation Authority

Northern Ireland
- Department for Infrastructure
- Department of Agriculture, Environment and Rural Affairs, incl. Northern Ireland Environment Agency
- Department of Communities
- Department for the Economy
- Department of Education
- Department of Finance
- Department of Health

Local authorities

Operational function

United Kingdom
- Heritage Lottery Fund
- Ministry of Defence (MoD)
- The Crown Estate
- The Oil and Pipelines Agency
- UK Financial Investments Ltd
- UK Government Investments

England
- East West Railway Company
- English Heritage / Historic England
- Environment Agency
- Forest Enterprise England
- High Speed Two (HS2) Limited
- Highways England
- Homes England
- LocatED
- London and Continental Railways Limited (LCR)
- National Forest Company
- Network Rail
- Planning Inspectorate

Scotland
- Forest Enterprise Scotland
- Network Rail
- Scottish Futures Trust
- Transport Scotland

Wales
- Economy, Skills and Natural Resources Group
- Natural Resources Wales
- Planning Inspectorate

Northern Ireland
- Department of Agriculture, Environment and Rural Affairs, incl. Northern Ireland Environment Agency
- Northern Ireland Transport Holding Company (Translink), incl. Ulsterbus, Metro and Northern Ireland Railways

Local authorities
- Crossrail Ltd
- Ebbsfleet Development Corporation
- National Parks UK*
- The Royal Parks
- Transport for London (TfL)

Technical function

United Kingdom
- Agriculture and Horticulture Development Board
- Civil Aviation Authority
- Industrial Development Advisory Board (IDAB)
- Joint Nature Conservation Committee
- National Infrastructure Commission
- Office of Gas and Electricity Markets
- Office of Rail and Road (ORR)
- Oil and Gas Authority (OGA)
- Regulatory Policy Committee
- Sea Fish Industry
- The Committee on Climate Change
- UK Government Investments
- Universities

England
- Building Regulations Advisory Committee (BRAC)
- Drinking Water Inspectorate
- Forest Commission England
- Natural Capital Committee
- Natural England
- Planning Inspectorate

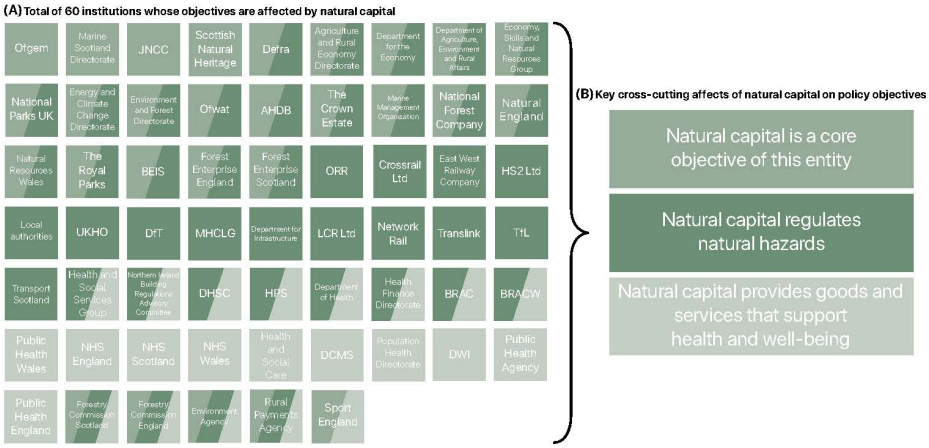
Scotland
- Convention of Scottish Local Authorities (COSLA)
- Forestry Commission Scotland
- Local Government and Communities Committee
- Scottish Natural Heritage (SNH)
- Transport Scotland

Wales
- Building Regulations Advisory Committee for Wales (BRACW)
- Drinking Water Inspectorate
- Natural Resources Wales
- Planning Inspectorate

Northern Ireland
- Department of Finance
- Northern Ireland Building Regulations Advisory Committee
- Northern Ireland Local Government Association (NILGA)

Local authorities
Transport for London (TfL)

* National Parks UK consists of 15 National Park Authorities (managed locally): Brecon Beacons, Broads, Cairngorms, Dartmoor, Exmoor, Lake District, Lock Lomond & The Trossachs, New Forest, Northumberland, North York Moors, Peak District, Pembrokeshire Coast, Snowdonia, South Downs and Yorkshire Dales.



Health and transport case studies

Department for Transport (DfT)

The UK Government Department of Transport (DfT) has a mission to:

- Provide policy, guidance and funding to English local authorities to help them run and maintain road networks, and develop new major transport schemes.
- Invest, maintain and operate the motorway and trunk road network in England through Highways England.
- Set the strategic direction for the rail industry in England and Wales through Network Rail.
- Improve English bus services through funding and regulation.
- Promote low carbon transport and new technology to decrease pollution.
- Support the maritime sector with an overall strategy and planning for ports in England and Wales.
- Set national aviation policy.

DfT can affect natural capital through its policy and planning, regulatory and financial functions to maintain and expand transport infrastructure and can be affected by natural capital through natural hazards as identified in **Figure 3**. DfT and other associated public-sector decision-making bodies identified in this review are mapped in **Figure 4**.

A review of all policy papers published by DfT between January 2015 and May 2018 identified that 35/115 of those papers (30.4%) can affect natural capital, while 18/115 (15.6%) were identified that can be affected by natural capital.

Some of the key policy papers identified in this review are:

Figure 3: (ABOVE) (A) public sector institutions affected by natural capital goods, services and associated risks, and (B) cross-cutting thematic classification of natural capital affects on delivery of institutional policy objectives. Detailed methods, results and institution abbreviations are documented in Annex 2.

- **High Speed 2** — HS2 is a new high-speed rail network connecting 8 out of the 10 largest cities in the UK. A number of policy papers discuss the impact of the project on the environment and how these environmental impacts are managed. [10,11,12]
- **Transport Infrastructure Efficiency** — this strategy complements existing efficiency targets and business plans. It discusses a variety of methods, including methods that can reduce environmental impacts at a significantly less cost. Highways England, for example, delivered the Smart Motorway Programme, generating faster and smoother journeys that can reduce air pollution.[13]
- **Transport Investment Strategy** — it sets out the HM Government objectives for investment in transport infrastructure across the UK. The strategy discusses the economic impacts of road congestion, estimating that as much as 28 million working days could be lost by 2040 under a high growth scenario. This strategy posits that 'transport infrastructure and its use bring a range of other environment impacts that need to be minimised and managed'.[14]
- **Cycling and Walking Investment Strategy** — it sets out the HM Government's ambition for walking and cycling and the objectives to move

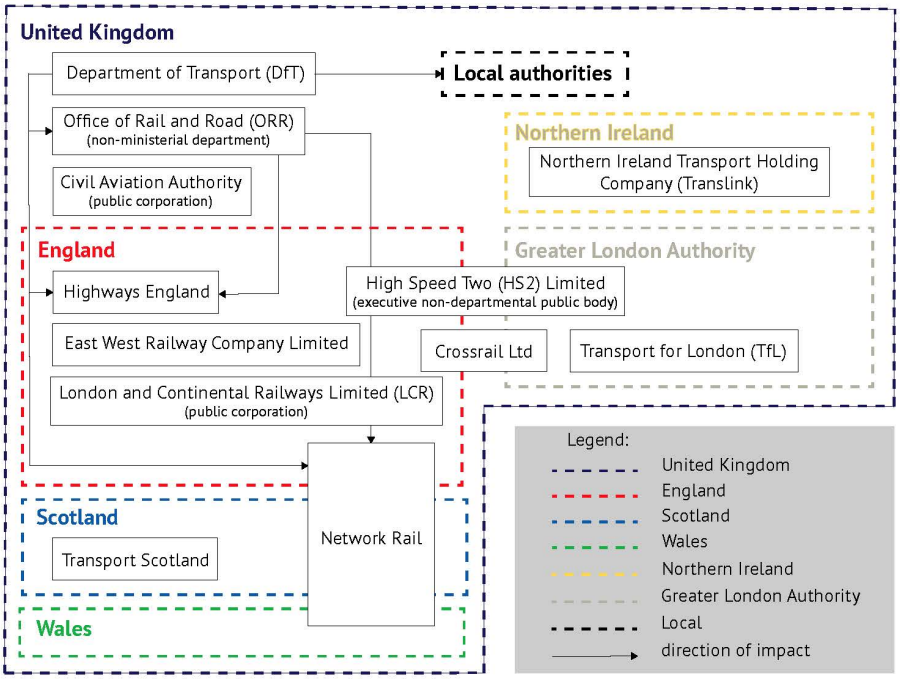


Figure 4: (ABOVE) Overview of UK public sector institutions associated with DfT. Arrows indicate the direction by which one institution could impact another, e.g. through financial, managerial or operational resources. Coloured and dashed lines indicate administrative boundaries.

closer to that ambition. It also sets out the financial resources, governance and performance monitoring arrangements available to support these objectives and describes a number of actions to support the delivery of this strategy. This strategy posits, for example, 'the importance of the wider built and natural environment being designed to make taking part in physical activity safer and easier'.[15]

- **Northern Transport Strategy** — this strategy sets out the strategy for improving transport across the north of England for railways, roads and freight. This strategy discusses, for example, the high-level assessment of the potential environmental impact of a road versus a tunnel under the Peak District National Park, considering potential noise, air quality and landscape impacts.[16]

Department of Health and Social Care (DHSC)

The UK Government Department of Health and Social Care (DHSC) has a mission to:

- Keep people healthy and support economic productivity and sustainable public services.
- Transform primary, community and social care to keep people living more independent, healthier lives for longer in their community.
- Support the NHS to deliver high quality, safe and sustainable hospital care and secure the right workforce.
- Support research and innovation to maximise health and economic productivity.
- Ensure accountability of the health and care system to Parliament and the taxpayer, and create an efficient and effective DHSC.
- Create value (reduced costs and growing income) by promoting better awareness and adoption of good commercial practice across the DHSC and our arm's length bodies.

DHSC can affect natural capital through its policy and planning, regulatory and financial functions to maintain and expand health and social care infrastructure such as building new hospitals. DHSC can be affected by natural capital through natural hazards and goods and services that support health and well-being as identified in **Figure 3**. DHSC and other associated public-sector decision-making bodies identified in this

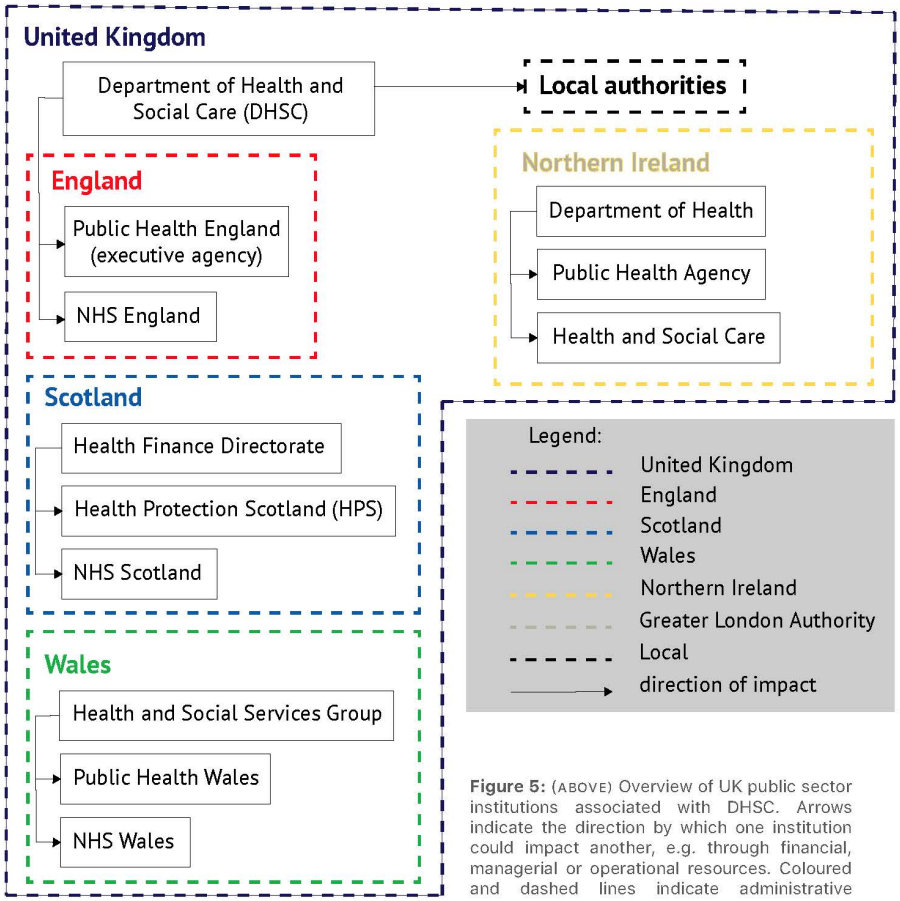


Figure 5: (ABOVE) Overview of UK public sector institutions associated with DHSC. Arrows indicate the direction by which one institution could impact another, e.g. through financial, managerial or operational resources. Coloured and dashed lines indicate administrative

review are mapped in **Figure 5**.

A review of all policy papers published by DHSC between January 2015 and May 2018 identified that 5/126 policy papers (4%) can affect natural capital, while 13/126 policy papers (10%) can be affected by natural capital. This suggests that DHSC is to large extent affected by natural capital assets without exerting much management responsibility over these assets.

Some of the key policy papers identified in this review are:

- **The NHS Mandate** — NHS Mandates of 2016-2017, 2017-2018 and 2018-2019 contain objectives to reduce inequalities (objective 1), support people to live healthier lives (objective 4) and improve out-of-hospital care to meet people's physical health, mental health and social care needs (objective 6).[17,18,19] Numerous studies have indicated associations between access to green spaces and physical, mental and social health.[20,21] The NHS Mandate's do not however make any reference to the role of the natural environment to deliver NHS's objectives.
- **The Naylor review** — this review and the Government response to the Naylor review discuss the opportunity to realise value from NHS property and deliver on DHSC objectives by releasing £2 billion of assets for reinvestment and delivering up to 26,000 new homes, potentially bringing about considerable land-use changes.[22,23]
- **Obesity** — a number of policy papers address the issue of obesity in children and adults, indicating that 'obese children are much more likely to become obese adults, and younger generations generations are becoming obese at earlier

ages and staying obese for longer'. These policy papers have made reducing childhood obesity one of their key priorities.[24,25,26,27] General understanding of associations between obesity and access to green space is well established.[28] The role of the physical environment for discouraging sedentary behaviour is addressed in most of these policy papers, there are however no actions formalised to address improvements of the physical environment, and thus indirectly supporting DHSC's objective to reduce obesity.

Expenditure as a cross-Departmental impact on natural capital

The expenditure of each public sector institution is an important component of its impact (or lack thereof) on natural capital. UK Government expenditure on natural capital is not yet comprehensively accounted for across Ministerial Departments and other public bodies. Environmental Protection Expenditure (EPE) has been calculated for different industries such as waste management, pollution abatement and protection of biodiversity and landscapes.[29]

HM Treasury provides data on total departmental spending for each ministerial department, however this does not give an overview of the direct and indirect spend on natural capital by central government and individual departments.

HM Treasury and Defra conducted a preliminary analysis in May 2017 to estimate government spend on natural capital.[30] This identified a direct spend on natural capital of £805 million by central government in 2015/2016. Central government was restricted in this analysis to DfT, Defra, Forestry Commission, Environment Agency, Natural England, Ministry of Defence and Ministry of Housing, Communities and Local Government. In relation to the £805 million, there are two prgrammes with an indirect spend on climate change (i.e. decarbonisation of heat and electricity, and low emission vehicles), increasing this value to £4.8 billion. This project showed that spending can be analysed through a natural capital lens and that direct spend on natural capital happens largely outside of Defra.

A 2015 report on greening government discussed environmental objectives by the UK Government and suggested that environmental departments alone (such as Defra) cannot guarantee cross-government action.[31] The report argued the need for government departments to have their own sustainable development strategy without feeling as if it were imposed on them.

A further breakdown of total departmental expenditure into non-environmental expenditure and environmental expenditure (i.e. expenditure that can affect natural capital such as building new roads or homes) would be valuable because (1) it would give an indication of the direct and indirect spend each institution has on natural capital and (2) help identify which institutions objectives have a significant impact on natural capital.

Policy implications and recommendations

These preliminary findings highlight the (1) considerable cross-cutting relevance of natural capital to UK public sector decision-making, and (2) the need to account for natural capital benefits and impacts in policy domains and institutions beyond those focused specifically on environmental policy and management.

Public administration and delivery of UK Government commitments concerning natural capital could be enhanced by bringing government stakeholders together through coordination structures and processes that feature broad cross-Departmental representation. Key tasks that these could focus on include: mainstreaming of natural capital considerations into financial expenditures and impact assessments, including appraisals and evaluations based on the new Green Book[4], and identification of priority natural capital assets relevant to policy delivery across Government.

The findings presented in this paper could be supplemented by future analyses that:

- Assess how environmental impacts and risks were identified in past impact assessments across Departments, in order to identify best practice, lessons learned, and methods for identifying 'win-win' scenarios for policy delivery and natural capital management.
- Identify, across different Departments, specific priority areas for cooperation and capacity-building concering natural capital.
- Further analysis of direct and indirect Government spending on natural capital assets, and attributable social and economic benefits.

Acknowledgements

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Annex 1 - Public sector impacts on natural capital condition

Methods

A high-level mapping was done of UK public decision-making entities that can affect natural capital. The following resources were used for the high-level mapping of UK public decision-making entities:

- Public bodies 2015: data directory.[8]
- United Kingdom Government website and other websites linked to it.[32]

Entities relevant to this project were included into further analysis. A description is given for each identified entity. Each entity was analysed through six questions:

1. What geographical jurisdiction does each entity in the UK act in? The following geographical jurisdictions are considered: United Kingdom (UK), England, Scotland, Wales, Northern Ireland and local jurisdictions.
2. What function does each entity exercise? All entities exercise a functional subset of activities. The different functions used in this paper are based on a consultation with UCL and Defra, and are generaly consistent with a policy mapping done by the Crown Estate.[33] The following functional activities were considered:
   i. Planning function: the entity thinks about and organises activities required to achieve a particular goal, involving the creation and maintenance of a plan. For example, the Planning Inspectorate deals with planning appeals, planning applications and other planning-related work for various types of infrastructure.
   ii. Regulatory function: the entity monitors, guides and controls particular public and/or private actors, which can include enforcing government controls and restricting a particular sector. For example, the Civil Aviation Authority regulates UK airline and airport safety standards, and security arrangements at UK airports.
   iii. Financial function: the entity manages money in such a manner to accomplish the objectives of the organisation. For example, HM Treasury controls public spending (including departmental spending), public sector pay and pension, annually managed expenditure (AME) and welfare policy, and capital investment.
   iv. Operational function: the entity brings together material and/or immaterial assets to produce a particular product or service. For example, Network Rail operates and develops Britain's railway, which includes tracks, bridges, crossings and stations to deliver well-functioning railway infrastructure to all its users.
   v. Technical function: the entity provides an advisory role to another entity, including the responsibility to manage and share data and statistics. For example, the UK Expert Committee on Pesticides provides technical advice to the government on the science relating to pesticides.

   Every entity can be considered to have exercise multiple functions as functions sometimes overlap. For example, the Environment Agency can produce a plan, as part of its planning function, that supports its operational function to manage a particular nature reserve.
3. Can this entity affect particular natural capital assets through its activities?
4. If this entity can affect natural capital, what habitat type(s) does it affect? The following habitat types are considered: Mountains, Moorlands & Heaths, Semi-natural grasslands, enclosed farmland, woodlands, freshwaters, urban, coastal margins and marine.[34]
5. Can this entity's cost-effectiveness of decision-making be affected by natural capital?
6. What overall sector does each entity act in? Based on the identified entities in this report, the following sectors were considered: transport, energy, health, economy, education, agriculture and natural resources, defence, housing and other.

Results

Results of the methods are available in full in the attached excel spreadsheet document.

Annex 2 - Natural capital impacts of public policy objectives

Methods

A high-level mapping was done of UK public decision-making entities that can be affected by natural capital. The following resources were used for the high-level mapping of UK public decision-making entities:

- Public bodies 2015: data directory.[8]
- United Kingdom Government website and other websites linked to it.[32]

Entities relevant to this project were included into further analysis. A description is given for each identified entity. Each entity was analysed through qualitative assessment of the following question: Can this entity's objectives be affected by natural capital?

A qualitative content analysis was undertaken on all entities whose cost-effectiveness of decision-making can be affected by natural capital to identify the key themes representing how natural capital can affect these identified entities. Elo and Kyngäs (2008) described in detail the qualitative content analysis process.[35] In summary, the qualitative content analysis contained three stages: (1) a short summary consisting of two or three sentences was made for each identified entity on how it is affected by natural capital, (2) these short summaries of each identified entity were summarised into a maximum set of three themes which can be either a word or a short sentence and (3) a final three key themes were identified for all identified entities together based on the themes of stage two. These results were refined through facilitated discussions between the two main authors of this paper until a consensus was reached.

Results

We found at least 60 entities that can be affected by natural capital. The qualitative content analysis summarises the ways by which an entity's objectives can be affected by natural capital into three key themes, i.e. (1) natural capital is a core objective of this entity, (2) natural capital regulates natural hazards and (3) natural capital provides goods and services that support health and well-being (Figure 6). Details of the results are available in full in the attached excel spreadsheet document.

The key theme 'natural hazards' was identified most often in this analysis with 46 out of 60 (76%) entities being affected by natural hazards according to this analysis. More than half of identified entities, 29 out of 60 (48%), whose body objectives can be affected by natural capital are connected to the key theme of 'natural capital is a core objective of this entity'. This means that their business is dependent on a well-functioning natural environment by definition. For example, the Environment Agency (EA) manages the environment in England. As management of natural capital is a core objective of this entity, a badly functioning natural environment will therefore by definition influence their business future decisions.[36] The last key theme 'natural capital provides goods and services that support health and well-being' was identified for 24 out of 60 (40%) entities.

Figure 6: (BELOW) (A) public sector institutions affected by natural capital goods, services and associated risks, (B) affects of natural capital on each of the identified public sector insitutions and (C) cross-cutting thematic classification of natural capital affects on delivery of institutional policy objectives.

(A) Total of 60 institutions whose objectives are affected by natural capital

United Kingdom
- Agriculture and Horticulture Development Board (AHDB)
- Department for Business, energy and Industrial Strategy (BEIS)
- Department for Digital, Culture, Media & Sport (DCMS)
- Department for Environment, Food and Rural Affairs (Defra)
- Department for Transport (DfT)
- Department of Health and Social Care (DHSC)
- Joint Nature Conservation Committee (JNCC)
- Ministry of Housing, Communities and Local Government (MHCLG)
- Office of Gas and Electricity Markets (Ofgem)
- Office of Rail and Road (ORR)
- The Crown Estate
- United Kingdom Hydrographic Office (UKHO)

England
- Building Regulations Advisory Committee (BRAC)
- Drinking Water Inspectorate (DWI)
- East West Railway Company
- Environment Agency
- Forest Commission England
- Forest Enterprise England
- High Speed Two (HS2) Limited
- London and Continental Railways (LCR) Limited
- Marine Management Organisation
- National Forest Company
- Natural England
- Network Rail
- NHS England
- Public Health England
- Rural Payments Agency
- Sports England
- The Water Services Regulation Authority (Ofwat)

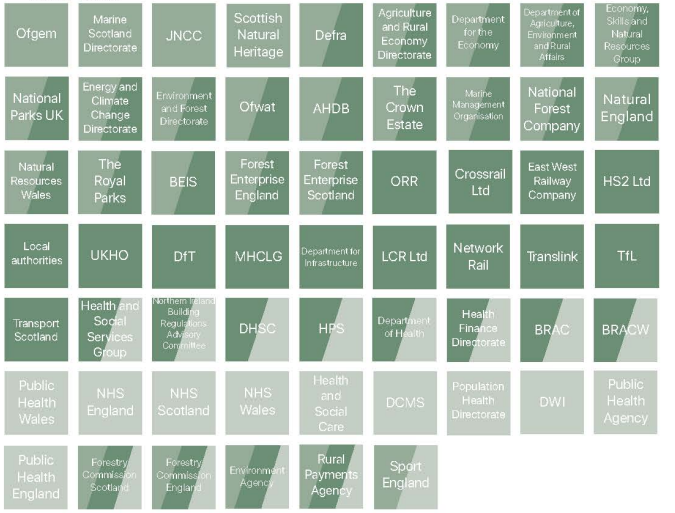
Scotland
- Agriculture and Rural Economy Directorate
- Energy and Climate Change Directorate
- Environment and Forest Directorate
- Forest Commission Scotland
- Forest Enterprise Scotland
- Health Finance Directorate
- Health Protection Scotland (HPS)
- Marine Scotland Directorate
- Network Rail
- NHS Scotland, incl. NHS Health Scotland
- Population Health Directorate
- Scottish Natural Heritage (SNH)
- Transport Scotland

Wales
- Building Regulations Advisory Committee for Wales (BRACW)
- Drinking Water Inspectorate (DWI)
- Economy, Skills and Natural Resources Group
- Health and Social Services Group
- Natural Resources Wales
- Network Rail
- NHS Wales
- Public Health Wales
- The Water Services Regulation Authority (Ofwat)

Northern Ireland
- Department for Infrastructure
- Department of Agriculture, Environment and Rural Affairs, incl. Northern Ireland Environment Agency
- Department for the Economy
- Department of Health
- Health and Social Care
- Northern Ireland Building Regulations Advisory Committee
- Northern Ireland Transport Holding Company / Translink
- Public Health Agency

Local authorities
- Crossrail Ltd
- National Parks UK
- The Royal Parks
- Transport for London (TfL)

(B) Affects of natural capital on each of the 60 institutions whose objectives are affected by natural capital



(C) Key cross-cutting affects of natural capital on policy objectives

Natural capital is a core objective of this entity

Natural capital regulates natural hazards

Natural capital provides goods and services that support health and well-being

Table D.1. Overview of public sector decision-making bodies in the United Kingdom (UK) for interlinkages with natural capital goods, services and associated risks.

See Figure 5.3 for the definition of National Parks UK and The Royal Parks. Local authorities were grouped together for the purpose of this analysis into one public sector decision-making body. PP = Policy and planning. R = Regulatory. F = Financial. O = Operational. TA = Technical and advisory.

Public sector bodies	Geographical jurisdiction	Function					Bodies who affect natural capital	Bodies whose cost-effectiveness of decision-making is affected by natural capital
		PP	R	F	O	TA		
Ministerial department								
Department for Business, Energy & Industrial Strategy	UK	X	X	X			X	X
Department for Digital, Culture, Media & Sport	UK	X	X	X			X	X
Department for Education	England	X	X	X			X	
Department for Environment, Food & Rural Affairs	England	X	X	X			X	X
Department for Transport	UK	X	X	X			X	X
Department of Health and Social Care	England	X	X	X			X	X
HM Treasury	UK	X	X	X			X	
Ministry of Defence	UK	X	X	X	X		X	
Ministry of Housing, Communities and Local Government	England	X	X	X			X	X
Non-ministerial department								
Agriculture and Rural Economy Directorate	Scotland	X	X	X			X	X
Department for Infrastructure	NI	X	X	X			X	X
Department for the Economy	NI	X	X	X			X	X
Department of Agriculture, Environment and Rural Affairs	NI	X	X	X	X		X	X
Department for Communities	NI	X	X	X			X	
Department of Education	NI	X	X	X			X	

Department of Finance	NI		X	X		X	X	
Department of Health	NI	X	X	X			X	X
Economic Development Directorate	Scotland	X	X	X			X	
Economy, Skills and Natural Resources Group	Wales	X	X	X	X		X	X
Education and Public Services Group	Wales	X	X	X			X	
Energy and Climate Change Directorate	Scotland	X	X	X			X	X
Environment and Forest Directorate	Scotland	X	X	X			X	X
Financial Strategy Directorate	Scotland		X	X			X	
Forestry Commission England	England					X	X	X
Forestry Commission Scotland	Scotland					X	X	X
Health and Social Services Group	Wales	X	X	X			X	X
Health Finance Directorate	Scotland	X	X	X			X	X
Housing and Social Justice Directorate	Scotland	X	X	X			X	
Learning Directorate	Scotland	X	X	X			X	
Marine Scotland Directorate	Scotland	X	X	X			X	X
Office of Gas and Electricity Markets	UK		X			X	X	X
The Water Services Regulation Authority	Eng. & Wal.		X				X	X
Office of Rail and Road	UK		X			X	X	X
Population Health Directorate	Scotland	X	X	X				X
UK Statistics Authority	UK		X			X		
Agencies & other public bodies								
Agriculture and Horticulture Development Board	UK					X	X	X
Building Regulations Advisory Committee	England					X	X	X
Building Regulations Advisory Committee for Wales	Wales					X	X	X
Centre for Environment, Fisheries and Aquaculture Science	UK					X		

Civil Aviation Authority	UK		X			X	X	
Committee on Climate Change	UK					X	X	
Convention of Scottish Local Authorities	Scotland					X	X	
Crossrail Ltd	Local				X		X	X
The Crown Estate	UK				X		X	X
Drinking Water Inspectorate	Eng. & Wal.					X	X	X
East West Railway Company	England				X		X	X
Ebbsfleet Development Corporation	Local				X		X	
Education Authority	NI				X		X	
English Heritage/ Historic England	England				X		X	
Environment Agency	England	X	X	X	X		X	X
Food and Environment Research Agency	UK					X		
Forestry England	England				X		X	X
Forest Enterprise Scotland	Scotland				X		X	X
Forest Research	UK					X		
Health and Social Care	NI			X	X	X		X
Health Protection Scotland	Scotland				X	X		X
Heritage Lottery Fund	UK				X		X	
High Speed Two Limited	England				X		X	X
Highways England	England				X		X	
Homes England	England	X			X		X	
Industry Development Advisory Board	UK					X	X	
Joint Nature Conservation Committee	UK					X	X	X
Local Authorities	Local	X	X	X	X		X	X
Local Government and Communities Committee	Scotland					X	X	

Local Government Association	Eng. & Wal.					X	X	
LocatED	England				X		X	
London and Continental Railways Limited	England				X		X	X
Marine Management Organisation	England	X	X	X			X	X
Met Office	UK					X		
National Audit Office	UK					X		
National Forest Company	England				X		X	X
National Infrastructure Commission	UK					X	X	
National Parks UK	Local				X		X	X
Natural Capital Committee	England					X	X	
Natural England	England					X	X	X
Natural Environment Research Council	UK					X		
Natural Resources Wales	Wales		X		X	X	X	X
Network Rail	GB				X		X	X
NHS England	England			X	X	X		X
NHS Scotland	Scotland			X	X	X		X
NHS Wales	Wales			X	X	X		X
Northern Ireland Building Regulations Advisory Committee	NI					X	X	X
Northern Ireland Local Government Association	NI					X	X	
Northern Ireland Statistics and Research Agency	NI					X		
Northern Ireland Transport Holding Company / Translink	NI				X		X	X
Oil and Gas Authority	UK		X			X	X	
Planning Inspectorate	Eng. & Wal.	X			X	X	X	
Public Health Agency	NI				X	X		X
Public Health England	England				X	X		X

Public Health Wales	Wales		X	X		X
Regulatory Policy Committee	UK			X	X	
Rural Payments Agency	England	X			X	X
Scottish Futures Trust	Scotland		X		X	
Scottish Natural Heritage	Scotland			X	X	X
Sea Fish Industry Authority	UK			X	X	
Sport England	England		X			X
The Oil and Pipelines Agency	UK		X		X	
The Royal Parks	Local		X		X	X
Transport for London	Local		X	X	X	X
Transport Scotland	Scotland		X	X	X	X
UK Expert Committee on Pesticides	UK			X		
UK Financial Investments Limited	UK		X		X	
UK Government Investments	UK		X	X	X	
United Kingdom Hydrographic Office	UK			X		X
Universities	UK			X	X	

Table D.2. Iterative qualitative conventional content analysis of the description of each public sector decision-making body

The content analysis contained three stages: (1) a short summary consisting of two or three sentences was made for each identified public sector body on how it can be affected by natural capital (NC), (2) the summaries of stage one were summarised into a maximum set of three themes which can be either a word or a short sentence and (3) a final set of three key themes were identified for all public sector bodies together based on the themes of stage two. Public sector decision-making bodies whose cost-effectiveness of decision-making was not identified to be affected by NC were excluded from the content analysis. See Figure 5.3 for the definition of National Parks UK and The Royal Parks. Local authorities were grouped together for the purpose of this analysis into one public sector decision-making body. Local authorities were grouped together for the purpose of this project. NI = Northern Ireland.

Public sector bodies	**Description**	**Qualitative content analysis (bodies affected by NC)**		
		Stage 1	**Stage 2**	**Stage 3**
Ministerial department				
Department for Business, Energy & Industrial Strategy (BEIS)	BEIS is to a large extent responsible to develop the UK's business, industrial strategy and energy infrastructure. To develop a low cost, clean energy system and develop UK industries, it can impact and is impacted by NC assets.	BEIS is impacted by NC assets as NC drives electricity generation of particular renewable energy infrastructure and natural hazards can disrupt/destroy infrastructures developed by BEIS.	- Electricity generation - Natural hazards disruption	- NC is a key issue for public sector bodies -¶NC regulates natural hazards - NC provides good and services that support health and wellbeing
Department for Digital, Culture, Media & Sport (DCMS)	DCMS is responsible to protect and promote the UK's cultural and artistic heritage and helps business and communities to grow by investing in innovation and highlighting Britain as a touristic destination. This includes overseeing the activities of e.g. historic England and the Royal Parks that directly affect particular NC assets. It also oversees activities related to sports for example. DCMS	DCMS is impacted by NC assets as NC can contribute to a better environment to partake in recreational activities that benefit physical and mental health.	- Human health impacts	

	can therefore affect and be affected by NC.		
Department for Education (DfE)	DfE is responsible for children's services and education in England with similar devolved departments (i.e. Department for Education (NI), Learning Directorate (Scotland) and Education and Public Services Group (Wales)). DfE carries final responsibility for maintaining and expanding the school infrastructure and therefore, it can impact NC.		
Department for Environment, Food & Rural Affairs (Defra)	Defra is the UK department responsible for safeguarding the natural environment with similar devolved departments (i.e. Department for Agriculture, Environment and Rural Affairs (NI), Economy, Skills and Natural Resources Group (Wales) and Environment and Forest Directorate (Scotland)).DEFRA carries final responsibility for managing the natural environment in England and the UK, including agricultural practices, flood protection and other natural hazards. Therefore, DEFRA can impact and is impacted by NC.	Defra is impacted by NC as NC drives agricultural productivity in the country, while its cost-effectiveness is impacted by definition by the natural environment and natural hazards can disrupt DEFRA's business of managing the natural environment and agriculture in the country.	- Agricultural productivity - Natural hazards disruption - The natural environment is a key issue
Department for Transport (DfT)	DfT works with numerous other agencies to manage the transport infrastructure in the UK. Several DfT responsibilities are important for NC:	DfT is impacted by NC as natural hazards can disrupt/harm DfT transport infrastructure.	- Natural hazards disruption

	(1) developing new major transport schemes, (2) maintaining and expanding the motorway and trunk road network in England, (3) funding rail industry and thus also expansion of new rail lines in England, (4) improving bus services in England and (5) promoting low carbon transport. These responsibilities can impact and are impacted by NC.		
Department of Health and Social Care (DHSC)	DHSC shapes and funds health and social care in England. It has similar devolved departments in other countries (i.e. Department of Health (NI), Health and Social Services Group (Wales) and Health and Social Care Integration Directorate (Scotland)). It has final responsibility for maintaining and expanding health infrastructure in England, which includes building new hospitals. In addition, several of its main management duties are impacted by NC such as physical activity of patients and mental health improvements. Therefore, DHSC can impact and be impacted by NC.	DHSC is impacted by NC as natural hazards can disrupt/harm health infrastructure and NC assets such as water quality and air quality can impact people's health and therefore disrupt DHSC's business of health improvement.	- Natural hazards disruption - Human health impacts
HM Treasury	HM Treasury is the government's economic and finance ministry. It oversees the delivery of infrastructure projects across the public sector and facilitates private investment into UK		

	infrastructure. It also provides guidelines for environmental valuation of projects through the Green Book: Appraisal and Evaluation in Central Government. Therefore, it can impact NC assets.		
Ministry of Defence (MoD)	MoD manages the UK armed forces defending the UK and its overseas territories. It manages a substantial part of the UK territory directly or through other agencies (e.g. The Oil and Pipelines Agency). Therefore, MoD can impact UK's NC.		
Ministry of Housing, Communities and Local Government (MHCLG)	MHCLG has the final responsibility to drive up the housing supply, increase home ownership, devolve powers and budgets to boost local growth in England and support strong communities with excellent public services. There are similar devolved departments in other countries (Housing and Social Justice Directorate (Scotland), Department of Communities (NI) and the Welsh Government).	MHCLG is impacted by NC as natural hazards can disrupt/harm the housing supply they are responsible for.	- Natural hazards disruption
Non-ministerial department			
Agriculture and Rural Economy Directorate	The Agriculture and Rural Economy Directorate is responsible for agricultural policy, rural land management, enhancing animal welfare and providing scientific services and advice on agricultural and	NC drives agricultural productivity in Scotland and natural hazards can disrupt/harm this body's role of providing policy and	- Agricultural productivity - Natural hazards disruption

	environmental matters. Therefore, it can impact and is impacted by NC.	managing agriculture and rural land.	
Department for Infrastructure	The Department for Infrastructure in NI is responsible for road improvement schemes, new transport initiatives, road and public transport, sustainable transport policies such as cycling and walking, maintaining waterways, etc… Therefore, it has an impact and can be impacted by NC.	NC can through natural hazards disrupt/destroy the transport infrastructure placed by this body.	- Natural hazards disruption
Department for the Economy	The Department for the Economy of NI is responsible for economic policy, polices and strategies on energy and developing a tourism strategy for Northern Ireland. Through these, it can impact and be impacted by NC.	NC drives electricity generation of particular renewable energy infrastructure and natural hazards can disrupt/destroy economic and energy infrastructures placed by this body.	- Electricity generation - Natural hazards disruption
Department of Agriculture, Environment and Rural Affairs	The Department of Agriculture, Environment and Rural Affairs in NI is responsible for biodiversity, countryside management, agriculture, forests, pollution and water. An executive agency within this department also manages the natural environment directly, called the Northern Ireland Environment Agency. Therefore, it can impact and is impacted by NC.	NC drives agricultural productivity in NI, while its cost-effectiveness is impacted by definition by the natural environment and natural hazards can disrupt/harm this body's role to manage agriculture and environment in NI.	- Agricultural productivity - Natural hazards disruption - The natural environment is a key issue

Department for Communities	The Department of Communities in NI is responsible for the housing supply, urban regeneration and social inclusion. Evidence suggests green infrastructure can improve social health in communities and support social inclusion. However, evidence for this is minimal. Therefore, it can impact NC.		
Department of Education	The Department of Education in NI is responsible for managing the school estate and building new schools and related infrastructure. Therefore, it can impact NC.		
Department of Finance	The Department of Finance in NI is responsible for Northern Ireland's public finances (which includes all public infrastructure expenditures), and promoting building regulations and energy efficiency of buildings (which includes potential areas adjacent to buildings outside). It also manages geospatial information for Northern Ireland. Therefore, it can impact NC.		
Department of Health	The Department of Health in NI is responsible for a strategic framework for public health, health promotion and guidance on how to manage the health business. They also have a strategy and action plan for mental health and learning disabilities, and provide	Natural hazards can disrupt/harm health infrastructure in NI and NC assets such as water quality and air quality can impact people's health and therefore	- Natural hazards disruption - Human health impacts

	advice on environmental health and climate change. Therefore, it can impact and be impacted by NC.	disrupt this body's role to improve health.	
Economic Development Directorate	The Economic Development Directorate is responsible to deliver Scotland's economic strategy, including boosting productivity. This could also include new economic areas for development. Therefore, it can impact on NC.		
Economy, Skills and Natural Resources Group	The Economy, Skills and Natural Resources Group in Wales focuses on a number of issues that can impact and be impacted by NC such as economic productivity and management of the natural environment in Wales.	Natural hazards can disrupt/harm the economic and environmental infrastructure in Wales and affect this body's role to provide policy and manage the economy and environment. Also, its cost-effectiveness is impacted by definition by the natural environment affects this body's role.	- Natural hazards disruption - The natural environment is a key issue
Education and Public Services Group	The Education and Public Services Group in Wales is responsible for a number of issues that can impact NC such as managing and expanding school infrastructure.		

Energy and Climate Change Directorate	The Energy and Climate Change Directorate is responsible to deliver a low carbon society. This includes a prosperous low carbon economy, sustainable energy, promoting its energy efficiency, climate change and clean energy programmes. Therefore, it can impact and can be impacted by NC.	NC drives electricity generation of particular renewable energy sources and natural hazards, including natural hazards because of climate change, can disrupt/harm energy and low carbon infrastructure supported by this body.	- Electricity generation - Natural hazards disruption
Environment and Forest Directorate	The Environment and Forest Directorate protects and enhances forests, landscapes, biodiversity, water and soils in Scotland. They are responsible for protecting Scotland's landscapes, habitats and biodiversity, ensuring woodlands and greenspaces are managed sustainably and ensuring pollution-free air and water resources. Therefore, it impacts and is impacted by NC.	The cost-effectiveness of this body is impacted by definition by the natural environment and natural hazards can disrupt/harm this body's role to manage the environment in Scotland.	- Natural hazards disruption - The natural environment is a key issue
Financial Strategy Directorate	The Financial Strategy Directorate is responsible for strategic financial issues, including infrastructure investment programmes and agreeing on and monitoring the administration budget. Therefore, it can impact NC assets.		
Forestry Commission England	Forestry Commission England plants trees all over England to create new woodland. They sustainably harvest wood from England and Scotland's public forests, managing over 900,000	The cost-effectiveness of this body is impacted by definition by the woodland and natural hazards can disrupt/harm the Forestry Commission	- Natural hazards disruption - The natural environment is a key

	hectares of land. They also check the health of trees from pests and diseases, provide grants to private landowners and protect species. Therefore, it impacts NC and is impacted by NC.	England's role to manage woodland. Disease outbreaks related to NC can also impact this body's role.	issue - Disease outbreaks
Forestry Commission Scotland	Forestry Commission Scotland protects and expands Scotland's forests and woodlands through guidance, grants and regulations and by shaping forestry policy in the country. Actual management of the estate is done by Forest Enterprise Scotland. Therefore, it impacts and is impacted by NC.	The cost-effectiveness of this body is impacted by definition by the woodland and natural hazards can disrupt/harm the Forestry Commission Scotland's role to manage woodland. Their role includes management of disease outbreaks from forests.	- Natural hazards disruption - The natural environment is a key issue - Disease outbreaks
Health and Social Services Group	The Health and Social Services Group focuses amongst others on health infrastructure in Wales, physical activity of citizens and improving wellbeing. Therefore, it can impact and is impacted by NC.	Natural hazards can disrupt/harm health infrastructure and NC assets can impact people's health (e.g. green space availability, water and air quality) and therefore disrupt this body's business of health improvement.	- Natural hazards disruption - Human health impacts
Health Finance Directorate	The Health Finance Directorate is responsible to make sure policy initiatives are effectively delivered and that health infrastructure is delivered as promised. This includes potential new hospitals. It is also responsible for reducing the carbon footprint of health service delivery and implementing the Healthcare Quality Strategy.	Natural hazards can disrupt/harm health infrastructure delivered by this body and NC assets can impact people's health (e.g. green space availability, water and air quality) and therefore disrupt this body's business of health improvement.	- Natural hazards disruption - Human health impacts

	Therefore, it impacts and can be impacted by NC.		
Housing and Social Justice Directorate	The Housing and Social Justice Directorate ensures that there are high-quality homes for all in Scotland. They are responsible for increasing the supply of homes. Therefore, it impacts NC.		
Learning Directorate	The Learning Directorate is responsible to ensure the school infrastructure is there for Scotland's learners. This includes providing sufficient schools. Therefore, it can impact NC.		
Marine Scotland Directorate	Marine Scotland Directorate is responsible for the integrated management of Scotland's seas. This includes compliance with fisheries regulations, promoting sustainable fisheries and sustainable management of fish resources. Therefore, it impacts and is impacted by marine NC.	The cost-effectiveness of this body is impacted by definition by the marine environment, impacting this body's role to manage Scotland's seas.	- The natural environment is a key issue
Office of Gas and Electricity Markets (Ofgem)	Ofgem protects the interests of electricity and gas consumers by promoting the security of supply and sustainability and regulating / delivering government schemes. Responsibilities include reducing greenhouse gas emissions, promote energy saving and support	NC drives electricity generation of particular renewable energy sources and therefore impacts Ofgem's role to secure energy supplies at all times.	- Electricity generation

	improvements in all aspects of the environment related to electricity and gas production / extraction. Therefore, it can impact and is impacted by NC.		
The Water Services Regulation Authority (Ofwat)	Ofwat ensures that private water companies properly carry out their functions and need to secure the long-term resilience of the water supply and wastewater systems. They must make sure water companies take steps to enable long-term resilience of water supplies and wastewater systems. Therefore, it can impact NC (through regulation of companies involved in upgrade and expansion of water and sewerage systems) and is impacted by NC (through water supply quality and quantity).	The cost-effectiveness of this body is impacted by definition by the natural environment (in this particular case water) and natural hazards can disrupt/harm Ofwat's role to provide and secure the water supply and wastewater systems.	- The natural environment is a key issue - Natural hazards disruption
Office of Rail and Road (ORR)	The ORR regulates the rail's industry health and safety performance. They hold Network Rail and HS1 to account, making sure it is competitive and fair. They also monitor Highways England and have regulatory functions to railways in Northern Ireland. Responsibilities with impact include ensuring Highways England delivers its major programme of investment for England's strategic road network, regulating Network Rail to ensure it delivers the performance and service needed and monitoring the	Natural hazards can disrupt/harm the transport infrastructure that the ORR indirectly regulates through its functions.	- Natural hazards disruption

	performance and efficiency targets of HS1.		
Population Health Directorate	The population Health Directorate provides policy advice, supports mental health services, aims to promote physical activity and other opportunities that have a positive impact on people's health and wellbeing. Therefore, it can be impacted by NC.	NC assets can impact people's health (e.g. green space availability, water and air quality) and therefore disrupt this body's business of health improvement.	- Human health impacts
UK Statistics Authority	The UK Statistics Authority is an independent body manages, creates and promotes official statistics for the government and public. It regulates changes to statistics and the quality of it, develops and informs on social and environmental matters and assists on the development and evaluation of public policy. It also supports HM Government and the NC Committee with NC accounting, assessing the value of UK's NC assets. Therefore, this body does not impact NC assets, but is impacted by NC assets.		
Agencies & other public bodies			
Agriculture and Horticulture Development Board (AHDB)	AHDB focuses amongst others on delivering extensive research and development programmes, raising awareness of food and ensuring government priorities are taken into account in the agriculture industry. It seeks to equip the industry with	NC drives agricultural productivity and natural hazards can disrupt/harm development programmes of the AHDB.	- Agricultural productivity - Natural hazards disruption

	practical information that can be applied to make better decisions and improve their performance, including environmental performance. Therefore, it can impact and is impacted by NC.		
Building Regulations Advisory Committee (BRAC)	BRAC is consulted upon by the Secretary of State when new proposals are made to make or change building regulations or related matters. This includes, health and safety, welfare and convenience of people in and around buildings, energy conservation and sustainability of buildings. Therefore, it can impact and be impacted by NC.	Natural hazards can impact building infrastructure and thus indirectly influences this body's role. NC also impacts people's health (e.g. green space availability) and therefore can affect this body's role to change building regulations and related matters.	- Natural hazards disruption - Human health impacts
Building Regulations Advisory Committee for Wales (BRACW)	Same as for BRAC	Natural hazards can impact building infrastructure and thus indirectly influences this body's role. NC also impacts people's health (e.g. green space availability) and therefore can affect this body's role to change building regulations and related matters.	- Natural hazards disruption - Human health impacts
Centre for Environment, Fisheries and Aquaculture Science (Cefas)	CEFAS provides innovative solutions for the aquatic environment, biodiversity and food security, working across of range of sectors such as aquaculture, fisheries, marine infrastructure, O&G and shipping. It		

	does not directly affect or is affected by NC.
Civil Aviation Authority	The Civil Aviation Authority works to meet the aviation industry's high safety standards, to manage security risks, to make efficient use of airspace and assess the environmental impact of aviation. This includes work to challenge the industry for greater action to reduce the environmental impact of its activity and have legal powers to provide information about the environmental impact of aviation. They also monitor noise levels around particular UK airports designated by the Government. Therefore, it can affect NC.
Committee on Climate Change (CCC)	CCC advises the UK Government on emission targets, on progress to reduce greenhouse gas emissions and preparing for climate change. Through its advisory role, I can impact policy fields that produce greenhouse gas emissions such as energy, production industries and transport. Therefore, it can impact NC.
Convention of Scottish Local Authorities (COSLA)	COSLA works with local councils in Scotland to improve local services and strengthen democracy. This includes in engaging with key financial, legislative policy developments and

	lead reforms that can improve local services. This can include local policy developments on local natural environment or other local projects that can impact NC.		
Crossrail Ltd	Crossrail Limited is responsible to build the new railway, known as the Elizabeth line, between Reading and Shenfield, and comprising a total length of 41 km. After completion it will be handed over to Transport for London. Therefore, it can affect NC.	Crossrail is impacted by NC as natural hazards can disrupt/harm its transport infrastructure.	- Natural hazards disruption
The Crown Estate	The Crown Estate is a specialist real estate business, managing 12.4bn GBP property portfolio. It is not the personal property of the Queen, but is owned by the Sovereign in right of the Crown. Besides managing land across the UK, it also is a key player in supporting the delivery of a diverse energy supply and mining particular minerals. Therefore, it can affect and is affected by NC.	Natural hazards can disrupt/harm the real estate owned and managed by this body. NC also drives electricity generation of particular renewable energy sources which is part of this body's role to deliver a diverse energy supply.	- Natural hazards disruption - Electricity generation
Drinking Water Inspectorate (DWI)	DWI approves and manages water company programmes for improving drinking water quality (which can include measures to improve the water source habitat). Therefore, it can impact and is impacted by NC.	NC can impact people's health through water quality which is part of this body's role to provide safe drinking water.	- Human health impacts
East West Railway Company	The East West Railway Company is a major project to establish a railway connecting East Anglia with central,	East West Railway Company is impacted by NC as natural	- Natural hazards disruption

	southern and western England. This includes the necessary purchase of new land to use for upgrading or expanding particular rail infrastructure. Therefore, it can impact NC assets.	hazards can disrupt/harm its transport infrastructure.
Ebbsfleet Development Corporation	Ebbsfleet Development Corporation speeds up the delivery of up to 15,000 homes in north Kent. This is set up by the UK Government and delivers core infrastructure for gas, electricity, water and highways. It cooperates closely with landowners to sell and purchase land where necessarily to ensure all infrastructure projects are delivered timely and within budget. Therefore, it can impact NC assets.	
Education Authority (EA)	EA in NI is responsible for ensuring that efficient and effective primary and secondary education services are available, and support the provision of efficient and effective youth services. This includes managing the number of available places in schools which through area planning can results in changes in school infrastructure. The EA holds responsibility for capital development and estate development of schools through funding of the Department of Education in NI. Therefore, it can impact NC.	

English Heritage / Historic England	English Heritage and Historic England engage people with heritage in England. It takes care of historic sites and artefacts (nearly 400,000 listings), which includes parks, gardens and shipwrecks. Therefore, it can affect NC.		
Environment Agency (EA)	EA primarily focuses on the natural environment in England and is responsible for regulating major industry and waste, treatment of contaminated land, water quality and resources, fisheries, inland river, estuary and harbours and conservation of species. Therefore, it can impact and be impacted by NC.	The cost-effectiveness of this body is impacted by definition by the natural environment and natural hazards can disrupt/harm the Environment Agency's role to manage the environment in England. NC also impacts people's health (e.g. water and air quality) which is also part of this body's role.	- The natural environment is a key issue - Natural hazards disruption - Human health impacts
Food and Environment Research Agency (Fera)	Fera is a national and international centre of excellence for interdisciplinary investigation and problem solving across plant and bee health, crop protection, sustainable agriculture, food and feed quality and chemical safety in the environment. It does not directly affect or get affected by NC.		
Forestry England	Forest Enterprise England manage England's Forest Estate, setting out the strategic direction of the organisation, monitoring the performance and managing any risks associated with	Natural hazards and the physical state of the environment can disrupt/harm the Forestry Enterprise	- The natural environment is a key issue - Natural hazards disruption

	managing England's forests. Therefore, it impacts and is impacted by NC.	England's role to manage woodland.	
Forest Enterprise Scotland	Forest Enterprise Scotland are an agency of the FCS and actually manage the National Forest Estate, giving strategic direction to 10 Scottish Forest Districts by designing and planting trees, marketing timber and providing public access. Therefore, it impacts and is impacted by NC.	Natural hazards and the physical state of the environment can disrupt/harm the Forestry Enterprise Scotland's role to manage woodland.	- The natural environment is a key issue - Natural hazards disruption
Forest Research	Forest Research is the Forestry's Commission agency for forestry and tree related research. It provides evidence and expertise to inform forest policies, provides innovative research, monitoring and scientific services and transfers knowledge with others. It does not directly affect or get affected by NC.		
Health and Social Care	Health and Social Care aims to provide the people of Northern Ireland with access to health and social care services provided by the National Health Service (NHS). It has a financial, operational and technical role (similar to NHS England, NHS Scotland and NHS Wales).	Health and Social Care is impacted by NC because it can impact people's health (e.g. green space availability) and therefore, it can affect this body’s role to improve the health and well-being of the people it serves.	- Human health impacts

Health Protection Scotland (HPS)	HPS plans and delivers effective and specialist services in Scotland to protect people from infectious and environmental hazards by providing advice, support and information. Part of its focus is directed towards gastrointestinal and zoonoses and environmental public health. Therefore, it can be impacted on by NC.	The cost-effectiveness of this body is impacted by natural hazards that can disrupt/harm this body's role. Disease outbreaks related to NC can also impact this body's role.	- Natural hazards disruption - Disease outbreaks
Heritage Lottery Fund	The Heritage Lottery Fund distributes the heritage share of National Lottery funding by supporting a variety of projects and has awarded >7.7 bn GBP to more than 42,000 projects across the UK. This includes over 3,200 projects funded to help conserve threatened habitats and species, and >850 public parks revitalised. Therefore, it can affect NC.		
High Speed Two (HS2) Limited	HS2 Ltd is responsible for developing and promoting the UK's new high-speed rail network. It is responsible for building and operating sustainably, responsibly and respectfully of the communities and places it affects. This body and its main role do impact NC.	HS2 Ltd is impacted by NC as natural hazards can disrupt/harm HS2 Ltd transport infrastructure.	- Natural hazards disruption

Highways England	Highways England is responsible to operate, manage and improve England's motorways and major A roads. This totals approximately 4,300 miles of road and represents 2% of roads in England by length. Highways England delivers 15 billion GBP of investment on the road network through the UK Government's Road Investment Strategy. Therefore, it can impact NC through maintenance and expansion of the road infrastructure in England.
Homes England	Homes England brings together land, money, expertise and planning to facilitate new homes. Most money is invested in building new houses. In fact, the investment from homes England helps build around half of all new homes in England. It owns public land which is sold to house builders. Therefore, it can impact NC in England.
Industry Development Advisory Board (IDAB)	IDAB advises ministers on applications from companies proposing capital investment projects in England. It provides advise on large business investment decisions, focusing on larger applications in England's Assisted Areas, although sometimes it also looks at other projects. It also looks at schemes of

	support in their development phase. This can include investment decisions that can impact NC such as factory expansions.		
Joint Nature Conservation Committee (JNCC)	JNCC provides evidence and advises so that decisions are made that protect natural resources and systems. They specifically work on nature conservation issues that affect the UK, informing policy development, providing objective advice and devising strategies for collecting and using data. They also play a role in the UK's marine nature conservation by identifying, monitoring and advising on protected areas and impacts of offshore industries. Therefore, it can impact and is impacted by NC.	JNCC is affected by NC as its cost-effectiveness is impacted by definition by the natural environment and can disrupt/harm this body's role to protect natural resources and systems.	- The natural environment is a key issue
Local Authorities	Local Authorities have a complex composition. Mostly, there are 2 tiers, i.e. county and district with responsibility for council services split between them. For example, England alone has 326 billing authorities that collect council tax and business rates. Responsibility of services can vary such as rubbish collection, recycling, housing, planning applications, education and transport. Therefore, local authorities can affect and be affected by NC.	Local authorities are affected by NC because natural hazards can disrupt a variety of services the local authorities support (e.g. housing or education). Local authorities are not impacted by the natural environment by definition, nor are they impacted by NC through people's health as this is more related to public health services.	- Natural hazards disruption

Local Government and Communities Committee	The Local Government and Communities Committee considers and reports on issues such as housing, planning, building standards and regeneration matters. Some of the issues it reports on can have impacts on NC.		
Local Government Association (LGA)	LGA contains 415 authorities for 2017/18 in England and Wales. It works for the councils to ensure a voice with the national government. They aim to influence national decisions on issues that matter to councils such as environment, waste, health, culture, tourism and planning services. Therefore, it can impact NC.		
LocatED	LocatED is a government-owned company that buys and develops sites for new free schools in England. It acquires land and buildings across England, making it one of the largest purchasers of land in the UK. Therefore, it can have an impact on NC.		
London and Continental Railways Limited (LCR)	LCR manages, develops and disposes of property assets within a railway context, particularly from major infrastructure projects. Through this, it drives regeneration projects to deliver homes and other HM Government objectives. Therefore, it can impact NC.	LCR Ltd is impacted by NC as natural hazards can disrupt/harm its transport infrastructure.	- Natural hazards disruption

Marine Management Organisation	The Marine Management Organisation licenses, regulates and plans marine activities in the seas around England. This includes managing and monitoring fishing fleet sizes and quotas for catches, planning and dredging with an environmental, economic or social impact, making marine nature conservation byelaws, dealing with marine pollution emergencies, helping prevent illegal fishing and enforcing wildlife legislation. Therefore, it can impact and is impacted by NC.	The Marine Management Organisation is impacted by NC because its cost-effectiveness is impacted by definition bt the marine environment it manages. Natural hazards can also disrupt/harm this body's role.	- The natural environment is a key issue - Natural hazards disruption
Met Office	The Met Office provides weather information and severe weather warnings. It also does research and delivers information to the Parliament. Although relevant to NC, it does not directly affect or get affected by NC.		
National Audit Office (NAO)	NAO scrutinises public spending for Parliament. It helps Parliament hold government to account and improve public services. This includes scrutinising policy related to environmental sustainability. Even though it does not directly affect NC or get affected by NC, this body could indirectly impact NC through its technical function.		

National Forest Company	The National Forest Company is responsible for the creation of the National Forest, a new wooded landscape across central England. It supports the creation and management of a resilient environment, encourages activities to promote forest-related business and engages with communities to improve wellbeing and quality of life. Therefore, it can impact and is impacted by NC.	The National Forest Company is impacted by NC because its cost-effectiveness is impacted by definition by the National Forest it is creating and managing. Natural hazards can also disrupt this body's role to manage the National Forest.	- The natural environment is a key issue - Natural hazards disruption
National Infrastructure Commission (NIC)	NIC produces reports and analyses with recommendations on infrastructure policy and strategy to support sustainable economic growth, improve competitiveness and quality of life in the UK. This includes a National Infrastructure Assessment in every Parliament, in-depth studies into infrastructure challenges and monitoring the government's progress in delivering infrastructure projects. Therefore, it can impact NC.		
National Parks UK	National Parks UK brings together the 15 National Park Authorities (local authorities). This includes national parks in England, Wales and Scotland. It promotes the National Parks, engages with the public the deepen the public's understanding. Although administered by its own local authority, they need to conserve and	National Parks UK is impacted by NC because its cost-effectiveness is impacted by definition by the national parks it manages. Natural hazards can also disrupt this body's role to manage the national parks.	- The natural environment is a key issue - Natural hazards disruption

	enhance the natural beauty and wildlife in the park and promote recreational opportunities in it. Therefore, it impacts and is impacted by NC.		
Natural Capital Committee (NCC)	NCC advises HM Government on NC assets. Thus, it provides advise on the sustainable use of NC, which covers the benefits derived from natural assets through the use of NC accounting techniques. Therefore, it can impact NC.		
Natural England	Natural England advises HM Government on the natural environment in England and helps protect England's nature. It does so by promoting nature conservation and protecting biodiversity, conserving and enhancing the landscape, and managing the environment to contribute in other ways to social and economic well-being. Therefore, it can impact and is impacted by NC.	Natural England is impacted by NC because its cost-effectiveness is impacted by definition by the natural environment it manages. Natural hazards can also disrupt this body's role to manage the natural environment.	- The natural environment is a key issue - Natural hazards disruption
Natural Environment Research Council (NERC)	NERC promotes and supports environmental observation and monitoring in environmental science through research. It seeks to advance knowledge and technology and generate public awareness of research outcomes through public engagement and dialogue. It does not directly affect or get affected by NC.		

Natural Resources Wales	Natural Resources Wales is responsible to advise the Welsh Government on issues relating to the environment and its natural resources, regulate the environment, including marine, forest and waste industries, respond to environmental incidents, manage Wales' natural resources (7% of Wales' land area) and monitor the environment. Therefore, it can impact and is impacted by NC.	Natural resources Wales is impacted by NC because its cost-effectiveness is impacted by definition by the natural environment it manages. Natural hazards can also disrupt this body's role to manage the natural environment.	- The natural environment is a key issue - Natural hazards disruption
Network Rail	Network Rail owns, operates and develops Britain's railway, including tracks, bridges, crossings and stations. Their role is to provide safe and reliable railway, manage and deliver projects every year, which can include upgrades and expansions to the existing network. Therefore, it has an impact on NC.	Network Rail is impacted by NC as natural hazards can disrupt/harm its transport infrastructure.	- Natural hazards disruption
National Health Service (NHS) England	NHS England sets out priorities and direction of the NHS. It shares out more than 100 billion GBP in funds, giving it a clear financial role in holding organisation to account for spending this money effectively for patients and efficiently for the taxpayer. it has an important operational and technical role, encouraging and informing the national debate to improve health and care.	NHS England is impacted by NC because it can impact people's health (e.g. green space availability) and therefore, it can affect this body's role to improve the health and well-being of the people it serves.	- Human health impacts

NHS Scotland	NHS Scotland sets out priorities and direction of the NHS. It has a yearly budget of more than 10 billion GBP, giving it a clear financial role. It has an important operational role, delivering health and care to the people of Scotland and also plays a technical role, for example through the NHS Health Scotland (NHS Special Board), to inform decision-making through evidence.	Similar to above	- Human health impacts
NHS Wales	NHS Wales aims to provide the people of Wales with access to health and social care services provided by the NHS Wales. It has a financial, operational and technical role (similar to above).	Similar to above	- Human health impacts
Northern Ireland Building Regulations Advisory Committee (NIBRAC)	NIBRAC advises the government of Northern Ireland on amendments to building regulations and other associated matters. This includes, health and safety, welfare and convenience of people in and around buildings and sustainability of buildings. Therefore, it can impact and be impacted by NC.	NIBRAC is impacted by NC because natural hazards can destroy building stock and therefore potentially disrupt/harm this body's role. It can also impact people's health (i.e. green space availability) and therefore can affect this body's role to change building regulations and related matters.	- Natural hazards disruption - Human health impacts
Northern Ireland Local Government Association (NILGA)	NILGA is the representative body for the 11 councils in Northern Ireland. It promotes, develops and champions local government by focusing on key		

	issues such as waste, planning and local economies. It has key working groups such as community planning and wellbeing, planning and regeneration and rural development. Therefore, it can impact NC.		
Northern Ireland Statistics and Research Agency (NISRA)	NISRA is the main source for official statistics and social research on Northern Ireland. They are responsible to produce and disseminate statistics and research to inform decision-making and improve understanding. This includes statistics on social and environmental matters. Therefore, this body does not impact NC assets, but is impacted by NC assets.		
Northern Ireland Transport Holding Company / Translink	The Northern Ireland Transport Holding Company or also called Translink is a parental company which includes subsidiary companies Ulsterbus, Metro and Northern Ireland Railways. It is responsible to deliver public transport services in Northern Ireland which includes operating bus and rail services, including cross-border and cross-channel links. The operations of Metro, NI Railways and Ulsterbus are managed by a single integrated Executive Team.	Translink is impacted by NC as natural hazards can disrupt/harm its transport infrastructure.	- Natural hazards disruption
Oil and Gas Authority (OGA)	OGA regulates, influences and promotes the UK oil and gas industry to maximise economic recovery of the		

	UK's oil and gas resources. This includes direct accountability for exploration and development decisions and approvals. Therefore, it can impact NC.		
Planning Inspectorate	The Planning Inspectorate deals with planning appeals, national infrastructure planning applications, examinations of local plans and other planning-related work in England and Wales. They are responsible to make decisions and provide recommendations on a range of land-use planning-related issues. They also implement government policy particularly for energy and transport and implement the government's aims of sustainable development through local planning. Therefore, it can impact NC.		
Public Health Agency	Similar to Public Health England and Public Health Wales, the public Health Agency is responsible in four key areas for Northern Ireland: health and social wellbeing improvement, health protection, public health support and research and development. Health protection can include protection and responses to public health hazards such as disease outbreaks. Therefore, it can be impacted by NC.	The Public Health Agency is impacted by NC because NC can impact people's health (e.g. water and air quality, access to green spaces) which is the main role of this body.	- Human health impacts

Public Health England (PHE)	PHE is responsible to make the public healthier and reduce differences between health of different groups. It does so by promoting healthier lifestyles, advising the government and supporting action by local government, the NHS and the public. It also protects the nation from public health hazards, prepare and respond to public health emergencies (including health emergencies such as zoonotic diseases) and improve the health of the whole population. Therefore, it can be impacted by NC.	PHE is impacted by NC because NC can impact people's health (e.g. water and air quality, access to green spaces) which is the main role of this body.	- Human health impacts
Public Health Wales	Public Health Wales is the public health agency of Wales and exists to improve health and wellbeing and reduce health inequalities for people. They provide advice, expertise and specialist services to the Welsh Government, provide public health knowledge and deliver to improve health and wellbeing outcomes and reduce health inequalities. This includes responses to public health hazards such as zoonotic disease outbreaks. Therefore, it can be impacted by NC.	Similar to above	- Human health impacts

Regulatory Policy Committee	The Regulatory Policy Committee provides the government with external independent scrutiny of new regulatory and deregulatory proposals. They rate the quality of evidence and analysis, check the estimates made to ensure decisions are made on the basis of a robust, evidence-based policy making process. This can include any regulatory or deregulatory proposals that can impact NC. Therefore, it can impact NC.		
Rural Payments Agency	The Rural Payments Agency pays out over 2 billion GBP each year to support the farming and food sector. Responsibilities include managing milk quotas, making payments for rural development schemes (including environmental stewardship), running cattle tracing services, carrying out 23,000 inspections each year, managing the Rural Land Register and enforcing horticultural marketing standards. Therefore, it can impact and is impacted by NC.	The Rural Payments Agency is impacted by NC because NC (e.g. pollination, soil fertility) drives agricultural productivity in the country. Disease outbreaks related to NC and natural hazards can also impact this body's role for carrying out inspections.	- Agricultural productivity - Natural hazard disruption - Disease outbreaks
Scottish Futures Trust	Scottish Futures Trust is an infrastructure delivery company owned by the Scottish government. They plan future infrastructure investments, improve the management of existing properties and deliver important infrastructure programmes.		

	This includes roads, schools, homes, hospitals and digital infrastructure. Therefore, it has an impact on NC.		
Scottish Natural Heritage (SNH)	SNH tries to secure the conservation and enhancement of natural and landscapes in Scotland. It tries to increase understanding of the natural environment and facilitates enjoyment of nature and landscapes. It advises on the sustainable use of management of nature and landscapes and tries to conserve, control and sustainably manage deer populations in Scotland.	SNH is impacted by definition by the natural environment as it is its core objective to conserve and enhance the natural environment in Scotland.	- The natural environment is a key issue
Sea Fish Industry Authority	The Sea Fish Industry Authority promotes the efficiency of the seafood industry. It is responsible to promote consumption, enhance reputation and inform decision-making. They also organise the Seafish Responsible Fishing Scheme (RFS) which is a voluntary vessel-based programme certifying high standards of crew welfare and responsible catching practices. This includes care for the environment through responsible practices (management of litter, lost fishing gear recovery and wildlife interaction records). Therefore, it can impact NC.		
Sport England	Sports England works to make people participate in sport or activity, regardless of age, background or	The cost-effectiveness of this body is impacted by definition by the natural environment	- The natural environment is a key

	ability. This also includes support for projects that encourage people to be physically active outdoors. Therefore, sports England does not affect NC, but the cost-effectiveness of its decisions can be affected by NC.	(through the simple presence of natural environments that can increase outdoor recreational and sports activities) affecting people's health.	issue - Human health impacts
The Oil and Pipelines Agency	The Oil and Pipelines Agency is responsible for the operation, maintenance and management of 6 Naval Oil Fuel Depots (OFDs) and one Petroleum Storage Depot. It managed the Government Pipelines Storage System until this activity was sold to Compañía Logística de Hidrocarburos (CLH). They aim to provide a marine fuel receipt, storage and delivery and manage and operate the facilities safely. These OFDs are located on UK coastlines. Therefore, it can impact NC.		
The Royal Parks	The Royal Parks aims to protect, conserve and maintain the royal parks, including the natural and designed landscapes and the built environment. They are also responsible to promote the Royal Parks, maintain and develop the biodiversity and support the advancement of education. Therefore, the Royal Parks can impact and are impacted by NC.	The cost-effectiveness of this body is impacted by definition by the natural environment (in this particular case the Royal Parks) and natural hazards can disrupt/harm the Royal Parks role to conserve and maintain parks.	- The natural environment is a key issue - Natural hazards disruption
Transport for London (TfL)	TfL is the integrated transport authority for the Greater London	TfL is impacted by NC as natural hazards can	- Natural hazards disruption

	Authority. They are responsible for London's public transport network and London's main roads, delivering transport capital investment into the Elizabeth line, modernising tube services, transforming the road network etc. The tube network also has one of the highest air pollution levels in London air quality. Therefore, it can impact and is impacted by NC.	disrupt/harm TfL transport infrastructure.	
Transport Scotland	Transport Scotland is responsible to deliver sustainable transport systems through the development of national transport projects, including projects in rail, road, canals and harbours. For example, during 2012-2015, it was allocated 5. billion GBP to invest in transport infrastructure and services. Therefore, it can impact NC.	Transport Scotland is impacted by NC as natural hazards can disrupt/harm its transport infrastructure.	- Natural hazards disruption
UK Expert Committee on Pesticides (ECP)	UK ECP is the follow-up from the Advisory Committee on Pesticides and provides independent, impartial advice to the government on the science relating to pesticides. Therefore, it does not directly affect or is affected by NC.		

UK Financial Investments Limited (UKFI)	UKFI is owned by the UK Government and manages a number of shareholdings commercially to create and protect value for the taxpayer as shareholder (e.g. The Royal Bank of Scotland Group plc and Lloyds Banking Group plc). It executes a strategy for realising value. The management of these shareholdings can include decisions on assets investments into the natural environment such as green infrastructure projects. Therefore, it can impact NC.		
UK Government Investments	UK Government Investments is wholly owned by HM Treasury and prepares and executes all significant corporate asset sales by the UK Government. For example, through taxpayer's money, the Green Investment Bank (GIB) was set up that funded and supported the developed of more than 100 green infrastructure projects in the UK. Therefore, through its activities, it can impact NC in the UK.		
United Kingdom Hydrographic Office (UKHO)	UKHO collects and supplies hydrographic and geospatial data for the Royal Navy and merchant shipping. Therefore, it does not impact but can be impacted by NC.	UKHO's fleet collects hydrographic and geospatial data that can be disrupted/harmed by natural hazards.	- Natural hazards disruption

Universities	Universities across the UK provide both technical advice and evidence to authorities on many issues including issues related to NC. Universities can also manage estates, including natural areas within these estates. Therefore, universities can impact and can be impacted by NC.	