Fostering nature-based solutions for smart, green and healthy urban transitions in Europe and China

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WP N°3 Mapping and modelling ecosystem services

CONCEPTUAL FRAMEWORK FOR MAPPING AND MODELLING ECOSYSTEM SERVICES

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EXECUTIVE SUMMARY

Cities are complex systems which encapsulate highly inter-connected and overlapping domains of built infrastructure, natural green and blue space components and interfacing all of this are people. Despite people being at the heart of everything that happens in cities, the role of people, and an understanding of who benefits (or not) from NBS tends to be addressed in a fragmented way in city policy and planning processes. There is a need for integrated approaches, which explicitly recognise the natural components and processes which underpin NBS and how they deliver ecosystem services. Such integrated approaches must also take account of how people interact with and benefit from NBS.

This report (in the form of a paper) aims to introduce and develop a conceptualisation of NBS, which at its core represents the complex interactions between natural components and people which are essential to providing ecosystem services, and in turn the interactions which are essential for managing the urban social-ecological system. In detail, we i) present a framework which places NBS in an urban context, acknowledging the contribution of natural capital and other forms of capital to NBS, and the interactions with people which deliver the ecosystem services and resulting wellbeing benefits in cities, ii) develop an internally consistent feature-based typology for NBS together with an evidence-based assessment of the functions that NBS provide, and iii) illustrate how an understanding of these interactions can be used to assess the multiple benefits that derive from different types of NBS. We conclude with recommendations on how to apply the framework in an urban planning context.

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TABLE OF CONTENTS

LIST OF FIGURES

1 INTRODUCTION

This report focuses on the conceptual understanding around how green and blue space (Nature based solutions – NBS) and people interact within a wider social, ecological and governance context in cities. It aims to enhance our understanding of these interactions, both between NBS and people at the level at which ecosystem services and benefits happen, and between this layer and the wider governance and societal structures in which NBS sit. These small-scale and large-scale interactions all determine how NBS are created and managed, and which ultimately help shape who is responsible for them, who receives benefits from them, and where and when this happens.

The deliverable takes the form of a paper submitted to a journal, and is structured accordingly.

2 URBAN GREEN AND BLUE SPACE AND PEOPLE – OPERATIONALISING A FRAMEWORK FOR ECOLOGICAL AND SOCIETAL CO-BENEFITS OF NATURE-BASED SOLUTIONS

DRAFT - For submission in Nature Based Solutions journal, February 2022

2.1 Abstract

Cities are complex systems which encapsulate highly inter-connected and overlapping domains of built infrastructure, natural green and blue space components and interfacing all of this are people. Despite people being at the heart of everything that happens in cities, the role of people, and an understanding of who benefits (or not) from NBS tends to be addressed in a fragmented way in city policy and planning processes. There is a need for integrated approaches, which explicitly recognise the natural components and processes which underpin NBS and how they deliver ecosystem services. Such integrated approaches must also take account of how people interact with and benefit from NBS. The objective of this paper is to introduce and develop a conceptualisation of NBS, which at its core represents the complex interactions between natural components and people which are essential to providing ecosystem services, and in turn the interactions which are essential for managing the urban social-ecological system. In detail, we i) present a framework which places NBS in an urban context, acknowledging the contribution of natural capital and other forms of capital to NBS, and the interactions with people which deliver the ecosystem services and resulting wellbeing benefits in cities, ii) develop an internally consistent feature-based typology for NBS together with an evidence-based assessment of the functions that NBS provide, and iii) illustrate how an understanding of these interactions can be used to assess the multiple benefits that derive from different types of NBS. We conclude with recommendations on how to apply the framework in an urban planning context.

Keywords: Nature based solutions (NBS); green space; green infrastructure (GI); co-production; ecosystem services

2.2 Introduction

Cities are complex systems which encapsulate highly inter-connected and overlapping domains of built infrastructure, natural green and blue space components and interfacing all of this are people. How to describe these (semi-)natural spaces in cities has many different conceptions (Taylor and Hochuli 2017), but they are increasingly defined as nature-based solutions (NBS). They encompass green space areas such as parks, street trees and grassland, blue space including rivers, ponds and the sea, as well as hybrid grey-green-blue infrastructure such as green roofs, green walls etc. NBS provides multiple benefits to city residents. These include reduction of potentially harmful exposures (air and noise pollution mitigation, urban heat island reduction, flood mitigation), building human capacities (opportunities for physical activity and social interaction) and restoring capacities (spaces for relaxation and recovering from stress), and the aesthetic contributions to quality of life (Cox et al. 2017). NBS can also provide educational, spiritual and nutritional benefits for residents (Tzoulas et al. 2007, Markevych et al. 2017), and promote mental health (Chen et al. 2019).

Despite people being at the heart of everything that happens in cities, the role of people, and an understanding of who benefits (or not) from NBS tends to be addressed in a fragmented way in city policy and planning processes. At a local-level and at the scale of individual interventions this is not always the case, and there are many examples where NBS design encourages consultation with local residents (e.g. (Bell et al. 2020)). In the most advanced examples, NBS may be co-designed and co-produced jointly with planners, residents, community groups, architects, local businesses, schools and other stakeholders (Lovell and Taylor 2013). However, at a strategic level, regional environmental planning tends to consider aspects of spatial patterns of green and blue networks, pressures and risks such as flooding, with the involvement of stakeholders and the public restricted to a local scale, although there are some notable exceptions (Grunewald et al. 2021). Decisions on where to place NBS interventions are often based on the locations where the pressure is greatest (the highest air pollution concentrations, the hottest areas, areas with the most frequent flooding), or where politics or co-financing decisions dictate the location. Yet a wider perspective, with a systematic assessment of benefits at a greater spatial scale and which considers the needs of city residents may lead to different decisions being made (Veerkamp et al. 2022). Rather than focusing on where the pressure is greatest, decisions could also take into account the number of people benefitting from an intervention, or the social and economic factors, which lead to enhanced levels of risk for certain sectors of the population, e.g. the elderly are more at risk of mortality from high temperatures (Gasparrini et al. 2012), or comparison of districts for numbers of residents being exposed to flooding and their social exposure to risk events (Weiland et al. 2011). There is a need for integrated approaches, which explicitly recognise the natural components and processes which underpin NBS and how they deliver ecosystem services such as flood mitigation, noise mitigation or carbon sequestration. Such integrated approaches must also take account of how people interact with and benefit from NBS, which are particularly relevant for cultural ecosystem services (Jones et al. 2016).

Another dimension to decision making on NBS planning is that it tends to be driven by single-issue problems, and lessons from complexity science are only slowly taken up in an urban health and well-being context (Gatzweiler et al. 2017). Examples include high air pollution concentrations at busy road junctions or hot spot areas of the city on hot days. Yet, one of the strengths of NBS above the standard technical built infrastructure solutions to such problems is that they provide multiple benefits (Lovell and Taylor 2013, Van den Berg et al. 2015, Salmond et al. 2016). The same trees that remove air pollutants also provide cooling and shade on hot days, can enhance interception and increase infiltration into the ground thereby reducing overland water flow, and provide shelter and food for insects and birds. They also provide recreational spaces, mental health and therapy, and opportunities for social cohesion and physical activity for urban residents across population groups. Therefore, understanding which set of benefits that particular types of NBS provide can give urban policy-makers and planners more opportunity to design interventions around specific problems, and to choose the locations for implementing that benefit a wider range of problems and urban citizens.

There are many typologies for NBS, which are mainly derived from satellite-based data processing, and/or publicly accessible mapping information (Koc et al. 2017) (Dennis et al. 2018). However, single-source approaches can have downsides. For example, satellite-based mapping captures broad classes of land cover such as trees, grass, water and built areas, but does not tell us what those features are used for, and cannot always delineate their boundaries (the classic land cover vs land use problem). By contrast, mapping of NBS features (typically from ground-based surveys) provides detailed maps of land use with accurate boundaries, but often misses detail on structural components, for example the extent of trees or of sealed surfaces within a cemetery. These features are often essential to understand and quantify some of the functions that the NBS can deliver such as carbon storage or air pollution removal. Greater benefit comes from typologies that combine elements of land use as well as land cover, since both are necessary to determine the combination of ecological and social functions that NBS provide, and their impacts on the well-being of urban residents (De la Barrera et al. 2016). Some typologies are also inconsistent in their application of categories, being a mix of feature-based and functional or activity classes (Baur et al. 2015). Ideally, a typology should be internally consistent, able to address functional and human use aspects, and be compatible with modelling approaches to calculate ecosystem services & benefits.

Hence, the objective of this paper is to introduce and develop a conceptualisation of NBS, which at its core represents the complex interactions between natural components and people which are essential to providing ecosystem services, and in turn the interactions which are essential for managing the urban social-ecological system. In detail, we i) present a framework which places NBS in an urban context, acknowledging the contribution of natural capital and other forms of capital to NBS, and the interactions with people which deliver the ecosystem services and resulting wellbeing benefits in cities, ii) develop an internally consistent feature-based typology for NBS together with an evidence-based assessment of the functions that NBS provide, and iii) illustrate how an understanding of these interactions can be used to assess the multiple benefits that derive from different types of NBS. We conclude with recommendations on how to apply the framework in an urban planning context.

2.3 The conceptual framework

2.3.1 Development of the framework

The conceptual framework was developed through a workshop and a series of follow-on activities among a multi-disciplinary team of researchers from natural science, humanities and social science, NGOs, city planners and NBS practitioners from Europe and China. The framework was designed to firstly capture and represent the following elements which were identified as important in complex urban systems, and secondly to be a tool which enables transformative thinking:

- Integration of people and nature
- Multi-functionality of green and blue space
- Scale (spatial and temporal aspects)
- Quality of green and blue space
- Co-production
- Governance and urban policy-making
- Education
- Incorporate pressures and drivers
- Focus on public and private interventions to create, manage or improve NBS

A number of frameworks were considered to guide this process. These included named frameworks such as eDPSEEA, DPSIR/ES, MAES, EKLIPSE as well as others (Maes et al. 2013, Morris et al. 2017, Raymond et al. 2017, Jones 2021). While the aim was to build on these as much as possible, they lack emphasis on some aspects which are particularly important in an urban context. Key limitations include the linear/circular nature of the vast majority of existing frameworks, which show people as end-users or receivers of a linear (or circular) sequence of processes, rather than as active participants in shaping and forming the service and benefit. In other words, co-production, and the dynamic nature of benefit, are inadequately addressed in most existing frameworks. A second aspect, which is particularly relevant to the consideration of NBS in urban settings is that most green and blue space is actually a complex mix of built infrastructure and natural capital. For example a green wall contains plants which are housed within a complex built infrastructure, which comprises artificial cells containing soil for rooting, a physical framework to support the plants while they spread, and an irrigation system to provide water and nutrients. The natural capital here is almost entirely dependent on the built infrastructure for its survival. Towards the other end of the spectrum for urban NBS, a large wooded park appears more natural but still has human input in the form of planting and maintenance of trees and lawns, and built infrastructure (such as surfaced paths, benches, cafes and toilet facilities) which inherently contributes to the potential of the park to provide multiple benefits. Therefore any framework needs to adequately recognise this combination of natural features and human elements.

2.3.2 Description of the framework

The framework (Figure 1) builds on insights from a number of studies. Its core elements are based on an existing framework which strongly emphasises co-production, and which explicitly recognises combinations of natural and human-centred capital (Jones et al. 2016, Jones 2021). Natural capital includes components linked to geology, soils (pedology), water, biodiversity and atmosphere. Human-centred capital encompasses (i) built capital (also sometimes called produced capital) like buildings or sewage infrastructure, (ii) human capital which is the embodied capital in people as well as the knowledge and skills they hold, (iii) social capital such as social networks, connections and mutually recognized practices, (iv) a relatively recent addition of cultural capital which covers peoples' value systems, perceptions, norms, identity and beliefs and (v) financial capital. More extensive definitions and examples of these forms of capital can be found in Jones et al. (2021). The framework has been broadened to place the mechanisms by which services and benefits are generated (Figure 1) into the wider context of urban settings (Figure 2). These include some of the challenges faced in urban areas, together with an understanding on which interventions can be made to improve the liveability of cities, ranging from those which are more NBS-focused to those which are more social-focused. We discuss below how the key components are represented in this framework.

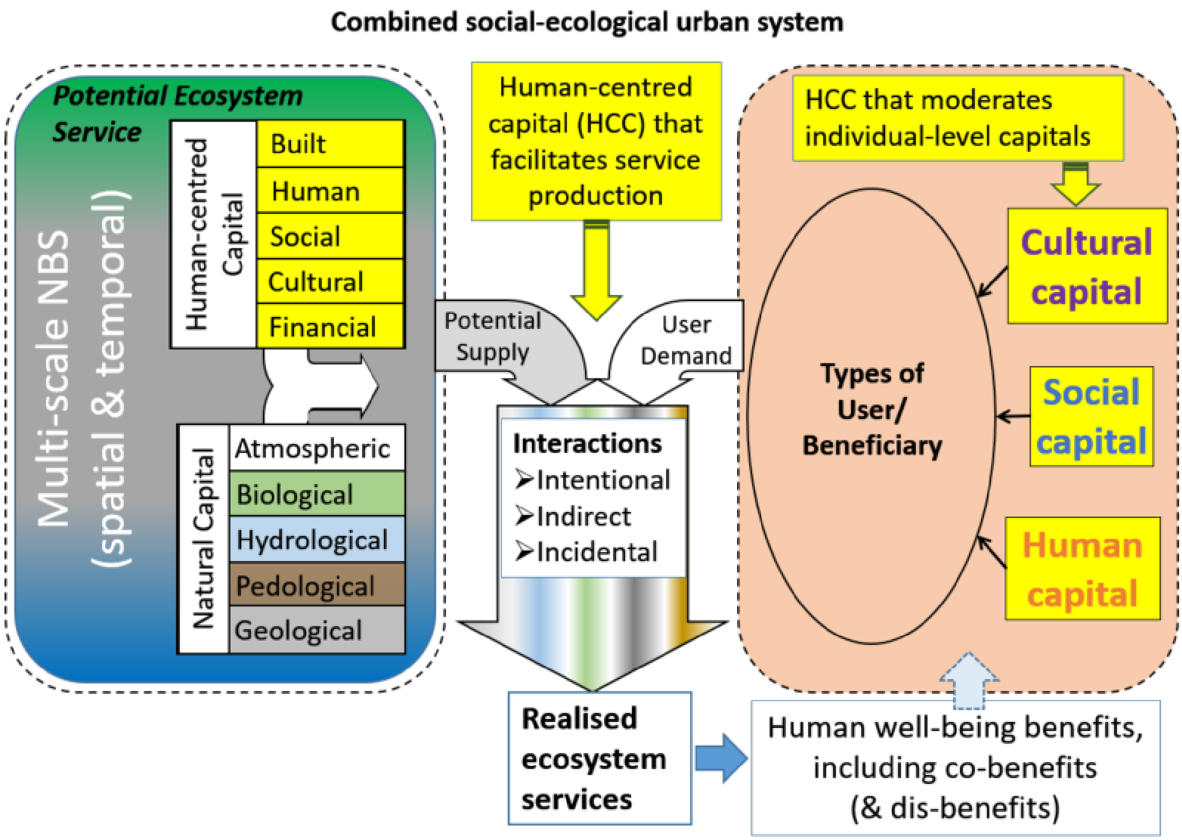

Figure 1: Conceptual framework for delivery of benefits by Green Infrastructure in urban settings, adapted from Jones et al. (2021).

2.3.3 NBS as an interaction between people and nature

Cities are a complex mix of green, blue and grey (i.e. built) infrastructure. We can define this through the framing of different types of capital. Using an urban park as an example, the natural capital within the park constitutes the geology and topography, the soil, biodiversity (flowers, trees, insect and animal species), water features (and their water quality) as well as the weather and their interactions (Fuller et al. 2007, Elliott et al. 2019, Börger et al. 2021). All of these influence how attractive the park is to a range of potential users. Human-centred forms of capital are also embedded within the park, and are extremely important in defining how much service that park can provide to users. This includes built capital elements, such as buildings, benches, trash bins, sealed paths which increase the user experience and accessibility and, if positive, lead to greater public use (Bancroft et al. 2015, Stessens et al. 2020). It also includes other forms of human-centred capital, which help maintain or govern the park: financial capital pays for maintenance of the park, human capital in the form of the gardeners who do that maintenance, social capital in the form of the capacity of institutions and governance mechanisms for the park, and cultural capital, which includes the public perception, norms and values associated with the park. This combination of natural and human-centred capital defines its potential as an NBS to provide a range of benefits to society. The quality of the NBS encapsulates this complete package of natural and human elements, and how well it provides a service to users. 'Quality' is a complex issue, and the attributes that determine quality may be different for each type of benefit that is provided, or for different types of park users. For example, woodland that provides the greatest noise mitigation will have closely planted trunks and will have a minimum width (Van Renterghem et al. 2012), but this may not support the highest biodiversity or the best opportunity for recreation.

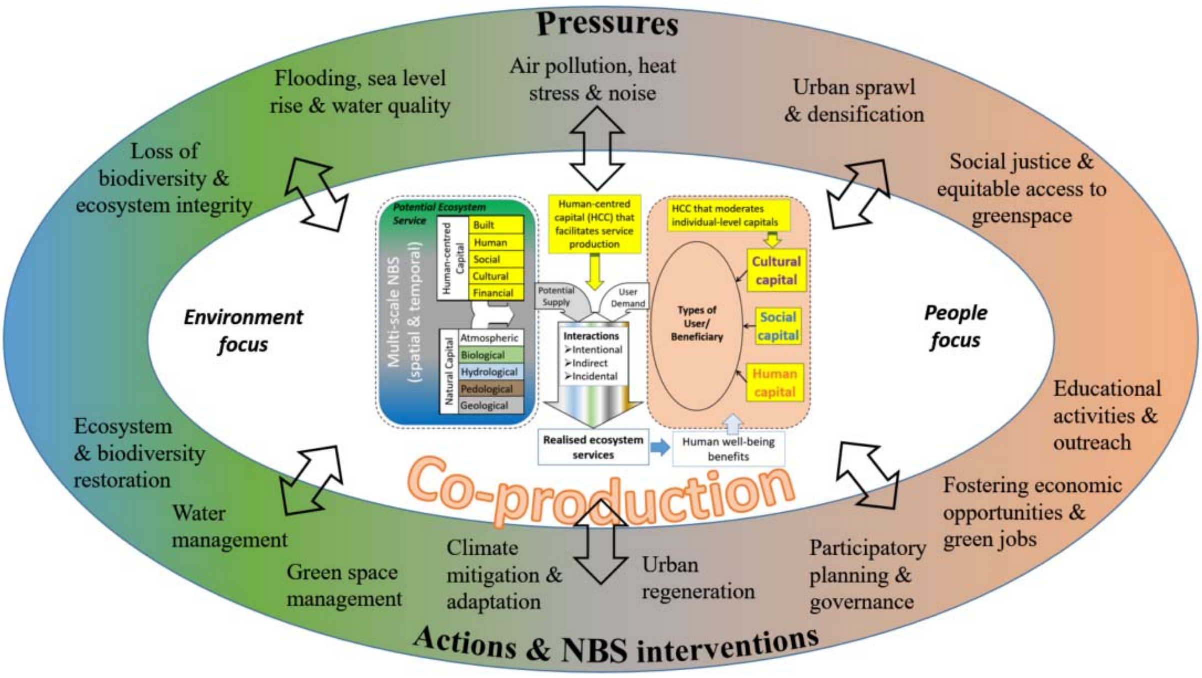

Figure 2: Conceptual framework showing how NBS actions can deliver solutions in response to pressures.

The left-hand side of Figure 1 therefore represents the potential for an NBS to deliver ecosystem services, for example a park which is open for public access. This can also be seen as a precondition or 'what is there' from the outset. The right-hand side represents users and beneficiaries, and the direct demand (actively wanting to walk in a park) or indirect demand (benefitting from carbon sequestration by trees in the park). The framework recognises that the benefit only happens from the combination of potential for a service to occur and the activated demand for it among users (when the two arrows meet in the middle). The 'realised' ecosystem service and the benefits are defined solely through the direct or indirect use of the park by people. To illustrate with an example for indirect demand, there is only a benefit of noise reduction by trees when there are users there to receive that benefit.

The nature of the interaction recognises that this can take different forms: Intentional, indirect and incidental, which are based on, but broader than, the definitions in Keniger et al. (2013). Intentional use might involve going to a park to relax after work, walking your dog in the park, or meeting family and friends there. Indirect use would include that trees in the park remove CO2 from the atmosphere, provide water retention or reduce the air pollution concentrations that you experience, and so the park contributes indirectly to your health and wellbeing. Indirect use also encompasses the more traditional definition of seeing a park through a window or viewing images of a park online. Incidental use covers where you travel past the park on your normal route to work and this exposure to greenspace contributes to your wellbeing. The framework also recognises that interactions of people with the NBS can result in multiple benefits or co-benefits, and potentially also some dis-benefits.

2.3.4 Types of users/beneficiaries

The box on the right side of Figure 1 represents beneficiaries. Here we define different 'types' of beneficiaries to capture characteristics which differentiate among categories of beneficiaries who may have different needs, or patterns of use of NBS. For example, are they socio-economically deprived, vulnerable (which may include children, elderly, disabled people), or do they live in particular areas of the city which increase their exposure to particular pressures such as noise or air pollution (Fairburn et al. 2019). Visitors to parks use them in different ways, and for different visit durations depending on whether they are local or have come from further away (Ayala-Azcárraga et al. 2019). Motivations may also differ according to the type of beneficiary, for example Home et al. (2012) found that younger residents visiting greenspace wanted to escape and reflect, while older residents were seeking social contact. All these different dimensions of beneficiaries' needs and desires will influence how NBS interventions can be designed, implemented and managed to improve access to benefits and well-being, and to minimise negative impacts.

2.3.5 Social and economic components - governance, business and education

The framework recognises that non-physical structures, systems, information flows and interactions can constitute specific forms of human-centred capital. Thus, governance is incorporated within policy institutions central to the decisions on, management and design of NBS (Kirsop-Taylor et al. 2021), and is therefore considered a component of social capital. Business can provide financial capital but can also innovate and provide input to the design, management and creation of new NBS by bringing together human capital in the form of knowledge as well as social capital through institutions or networks set up to create or manage novel NBS (Mayor et al. 2021). Education can feature in many ways. Teaching is a form of interaction itself designed to transfer human capital in the form of knowledge, but can also make intentional, indirect and incidental use of the awareness and educational benefits provided by green and blue space as part of the teaching process (Lerstrup and Konijnendijk van den Bosch 2017).

2.3.6 Drivers/pressures, actions & interventions

Drivers and pressures influence the combined social-ecological system, and for convenience we refer to them collectively as pressures. The pressures listed in Figure 2 are not exhaustive, but cover some of the main challenges affecting urban areas. They include increased population growth leading to growth and change in city extent and form as well as increased demand for ecosystem services. They also include pressures linked to air, water and climate, as well as social factors such as increases in social inequity, and the breakdown and loss of cohesion of urban neighbourhoods, health and wellbeing. Loss of biodiversity is framed as a pressure here, in the same context as poor air or water quality or increased risk from flooding, but these could alternatively be seen as an impact of the pressures, and therefore an emergent property of impacts on the city system.

The actions and interventions are human management responses and levers to create a positive change in the system. Thus, interventions can focus on the biophysical components of the NBS (creating species-rich grassland on road verges, planting trees near a school for educational purposes), on the built capital components of the NBS (toilets in a park, a cycle path along a canal, managing public space next to the sea (Bell et al. 2020)), but also on the demand side or governance of the system to increase the use, perceptions or desirability of an NBS in the eyes of beneficiaries. The framework makes clear that both pressures and actions can operate on any part of the system.

2.3.7 Co-production

In our framework co-production is central to the interactions among people and institutions that take place around the design and management of NBS. Co-production is a participatory policy-making and/or planning process in which people, as citizens, communities and/or users, not only are consulted but are offered a role as genuine participants in the whole process, from exploratory reflections, conception of the issue, decision making, design of potential solutions, implementation and evaluation (Pestoff 2012). Thus in the diagram, co-production encompasses those interactions among people, governance institutions, financing agencies and those who are end users in order to address these urban challenges. Ultimately, this should result in better quality NBS which meet the needs of urban dwellers, biodiversity and reduce the adverse impact of urban challenges.

2.3.8 Holistic framing

Overall, this allows a more flexible and less constrained understanding of what constitutes NBS. Previous definitions have taken a very biophysical definition of NBS (what it is), or functional definition (what it does) (Faivre et al. 2017). Here we define the NBS to incorporate its full physical structure (including built capital), but also the human interactions, public perceptions and governance structures which enable it. In this way, a functioning NBS, which truly provides benefits means not only that the bio-physical structures are in place, but also that people are able to interact with or use it. Underpinning the framework is a recognition of the complexity of scaling effects. Temporal and spatial scales can moderate or influence the benefits that NBS provide, and those benefits may be dependent on the scale at which different ecological and social processes operate (Hutchins et al. 2021).

2.4 A feature-based NBS typology

In order to operationalise the framework, a consistent typology of NBS types (the left hand part of the diagram in Figure 1) was required. A typology based on NBS features was selected as the most appropriate approach, since this allows separate cross-matching of individual NBS features with their ecological and social functions to provide a matrix of NBS and benefits for society.

The typology (Figure 3) combines aspects of land use and land cover, and was designed to facilitate planning and assessment of benefits to city dwellers by city authorities. Thus, the components include features such as gardens and parks which might feature in a planning database, as well as land cover types outside of mapped/delineated features, such as riparian woodland, or non-specified areas of grassland, brownfield sites, shrubland or woodland. The typology is relevant for most temperate and humid tropical urban systems but may need adapting for urban contexts in more extreme arid or cold bioclimatic zones.

The typology has nine main categories, further broken down into 46 sub-categories. They range from small features (balconies or gardens) through to much larger features (parks, urban woodland). The main categories cover a mix of private and public space, and individual sub-categories may contain examples of each. Land ownership can severely restrict public access to many benefits provided by urban NBS, particularly in urban areas where space is under high demand and every parcel of land tends to be clearly demarcated as public or private (Landry and Chakraborty 2009, Andersson et al. 2019). Therefore, overlaying data on public/private ownership, as well as socio-economic data allows more nuanced assessments of how benefits are delivered to different groups in society in particular locations (Nesbitt et al. 2018). This allows separate calculation of the benefits which come from direct use of NBS, where access is controlled by ownership (e.g. a communal garden area within a gated housing development) and therefore the physical health benefits that would come from exercising in that garden. In such cases, most of the indirect benefits (from the air pollution removal that the garden provides) are still provided, and some of the incidental benefits where such NBS are visible from other locations (lowered stress levels as a result of seeing flowering trees over the wall as you walk past on the pavement).

The typology is designed to be flexible to accommodate different land cover data sets and the modelling approaches which can be used to quantify ecosystem services and resulting benefits to city dwellers. Therefore, a cemetery can be classified as a type of public space which is accessible to the public, with a defined boundary, thus describing its land use, but land cover can be overlaid in order to assess how the component land cover classes within it (trees, grass, sealed surfaces) combine to deliver different amounts of service.

Brief description	Object type	Object category
Mainly public space, but some access restrictions may apply	Parks	Pocket park
		Park
		Botanical garden
		Heritage garden
		Nursery garden
Civic areas designed primarily for specific amenity uses	Amenity areas	Sports field
		School yard
		Playground
		Shared open space (not green)
Mainly civic areas designed primarily for specific uses (not primarily leisure)	Other public space	Cemeteries
		Allotment/shared urban growin
		City farm
		Adopted public space
Linked to transport and access	Linear features/routes	Street tree
		Cycle track
		Footpaths, including along wate
		Road verge
		Riparian woodland
		Hedges
Constructed green and blue space, added to infastructure	Constructed GBS on top of infrastructure	Green roof
		Green wall
		Roof garden
		Pergola
Infrastructure designed to incorporate some GBS components	Hybrid GBS (for water)	Permeable paving
		Permeable walkway
		Permeable roadway
		Permeable parking
		Attenuation pond
		Flood control channel
		Rain garden
		Bioswale
Bluespace features	Wetlands	Wetland
		River/stream
		Canal
		Pond
		Lake
		Reservoir
		Estuary/tidal river
		Sea
Other un-sealed features without specified use, often on private land	Other non-sealed urban areas	Woodland (other)
		Grass (other)
		Shrubland (other)
		Sparsely vegetated land

Figure 3: Components and descriptions of the main and sub-classes of the typology.

2.5 Ecosystem service and wellbeing delivery by typology components

The multiple ecosystem services and benefits that are provided by urban NBS are frequently cited in the literature. However, for many NBS components, there is relatively little published evidence, or their ability to deliver services has only been assessed for one particular function, and not for multiple ones. Therefore, there exists considerable knowledge gaps on the potential for multiple ecosystem service delivery for most NBS in an urban context. We used a multi-disciplinary expert panel to derive an expert-based assessment of delivery of all NBS components in the typology against a set of key ecosystem services in urban areas. These span a range of provisioning services (food production), regulating services (mitigation of poor air quality, noise, heat, water quality, flooding, carbon sequestration) and cultural services linked to physical and mental wellbeing (providing opportunities for physical health, social interactions, restoring capacities), as well as the potential to support biodiversity.

The assessment is based on the following principles. Ecosystem service delivery is expressed per unit area of the NBS, which allows direct comparability across different components. Taking the size of NBS interventions into account can happen in subsequent analysis. Scores assume an average or typical set of components across a city. For example, private gardens range from fully paved over with impermeable surfaces to a mix of grassy areas with flowers and sometimes trees. The assessment for gardens takes an overview of these forms to assess the level of service that the average garden space provides, taking into account this variation across a city. This assessment is conducted assuming a typical city in temperate Western Europe, and may need to be adjusted for cities in other parts of the world, especially in different climatic zones and very different social contexts. When considering the potential for ecosystem services delivery it is assumed that the public are able to access the space, unless the component is specifically defined as private space such as balconies. Thus, for those services where public access is required in order to provide benefit the scores assume full accessibility. Where there is no public access or where access is restricted in some way (communal gardens within gated communities), the scores should be adjusted accordingly when applying the framework. Assessment is based on relevant published evidence of benefits, and working from first principles to extrapolate from an understanding of the basic underlying ecological, hydrological and social mechanisms involved, in order to fill in the gaps for less-studied NBS components. Cultural service benefits to people are separated into three categories: opportunities for physical exercise, social interactions and restorative benefit. In those assessments, activities, which take place alongside some features (particularly blue features like rivers, lakes or the sea), are assumed to be in large part due to those blue features, even if the activity itself does not take place on or in the water. The literature on which the assessment is based is discussed in the following sections.

2.5.1 Food provisioning

NBS in urban areas provide a range of opportunities for food provisioning, ranging from cultivated areas to informal gathering of wild food. Formal food production in urban habitats occurs primarily in private gardens, community-supported agriculture, community allotments and gardens. In some countries, food cultivation also takes place on vacant lands and in public parks. City farms and allotments can be a significant source of locally grown food (Speak et al. 2015), and food provisioning from city farms and allotments is scored ‘very high’. Private or shared space such as gardens are scored 'medium' since they can support food production but the overall area devoted to food is usually low, with an emphasis on ornamental plants and areas for rest and relaxation. Although food production using high technology soil-less systems on roof space can be very efficient (Orsini et al. 2014), this is not considered an NBS and green roofs are scored 'negligible'. The more extensive green roof technology which underlies roof gardens is scored 'medium', since they have potential for production of fruit, vegetables and honey (Whittinghill and Rowe 2012), but the majority are used for recreation and relaxation rather than food production. Planted trees, either as single street trees or in other urban wooded settings, and other habitats such as shrubland, grassland or hedges may provide fruit and nuts, berries, herbs and fungi (Park et al. 2019, Nicholls et al. 2020), but the majority of species are ornamental, and the urban natural areas are often over-managed, and so are scored 'low' for this service (Salbitano et al. 2016). Foraging also applies to blue space, where streams, lakes, ponds and coastal waters can be used for fishing, shellfish or seaweed collection (Shackleton et al. 2017). The sea (including beaches) and estuary/tidal river are scored 'high', lakes 'medium' and rivers, canals and reservoirs 'low', mainly as a function of their naturalness and ability to sustain these practices over longer time scales. Overall, there is substantial potential to increase urban food production, but there also concerns around contaminants such as heavy metals and organic pollutants in urban soils (Park et al. 2019) and water bodies (Jang and Chen 2018, Joosse et al. 2021).

2.5.2 Air pollution removal

The potential for vegetation to remove pollutants from the air, and the resulting reduction in exposure of the population and associated health benefit to people, differs depending on the pollutant involved and the principal mechanisms operating (Nemitz et al. 2020). Removal of gaseous pollutants such as NO2 and SO2 occurs mainly by stomatal uptake, while removal of fine particulate matter such as PM2.5 is dominated by dry deposition to surfaces (Janhäll 2015). From a health perspective, particulates and NO2 are generally considered the most damaging in an urban context, although it is difficult to separate their effects using epidemiological approaches because they have common sources. The largest health benefits due to removal of urban pollutants by vegetation were associated with fine particulate matter (PM2.5) (Jones et al. 2019), therefore this assessment focuses on mechanisms which remove PM2.5, and on the resulting changes in pollutant concentrations, rather than the weight of pollutant removed. Dry deposition of PM2.5 is a function of leaf area index, roughness length, as well as pollutant concentrations and overall area of vegetation (de Jalón et al. 2019). This assessment considers per unit area performance, and therefore focuses on leaf area index of NBS types. Trees have a high leaf area index and roughness length and are more efficient at removing particulate matter than lower vegetation such as grass or other surfaces including water and built infrastructure (Asner et al. 2003), therefore NBS types which are predominantly made up of large trees, such as woodland, were assigned the highest category of 'very high'. Street trees are typically smaller in size than woodland trees (Monteiro et al. 2020) and so were assigned a value of 'high', as were parks and greenspace that contain some trees but mainly with a moderate to low overall percentage. NBS types made up of lower vegetation, or with generally few trees, like gardens were assigned 'medium' while predominantly grassy areas and green roofs were assigned 'low'. Surfaces which are predominantly un-vegetated, such as permeable paving were assigned 'negligible'.

2.5.3 Noise mitigation

NBS can mitigate noise via two main mechanisms: i) by absorbing the energy of the sound pressure waves, and ii) by redirecting and scattering the sound waves; acting as a shield in front of receptor locations such as, for example, residential buildings. The redirection and scattering of sound leads to the sound pressure level (measured in decibels, and typically expressed as dBA – decibels weighted to the hearing range of the human ear) diminishing as the sound wave spreads out over a larger area. Energy is also lost in the form of heat as the wave propagates through the air. Considering the example of trees, the soft green vegetation (i.e. leaves) can absorb some of the energy, although this is largely confined to high frequency components (Tang et al. 1986, Van Renterghem et al. 2014), whereas the larger woody structures (i.e. trunks and stems) reflect and scatter the sound. Because the ground under trees tends to be relatively soft, more energy is absorbed here than if it were a hard surface, such as bitumen, or concrete (Van Renterghem et al. 2012). Although a limited amount of mitigation is provided through direct absorption (higher frequencies), the majority comes from the redirection and scattering of sound, hence the NBS that has the most substantial effect involves trees. Parks, large gardens and areas of woodland (including riparian trees) will tend to provide the greatest level of mitigation, which is dependent on the density of trees and the depth, perpendicular from the noise source (e.g. a noisy road), and so are scored 'very high', 'high' or in some cases 'medium', depending on the typical coverage and density of trees in these features. Other typology components which lack trees or barriers of an adequate height between the noise source and people typically score 'low'. Due to the absorbance of sound by the ground, all surfaces of low height that are not sealed in some way with tarmac, stone, concrete or heavily compacted substrates score 'low', while sealed surfaces are scored 'negligible'. Water bodies can provide masking natural noise, particularly where moving water is a feature (Brown and Muhar 2004, Nilsson and Berglund 2006). Therefore rivers and the sea are scored 'high' due to moving water, larger water bodies such as lakes and reservoirs score 'medium' due to noise from waves, while still or slow-moving water bodies like canals score 'low'. Green roofs score 'negligible' as they are not located where they can intercept noise in-between noise sources and people.

2.5.4 Heat mitigation

Heat mitigation by NBS occurs through a number of mechanisms, primarily increased evapo-transpiration and shading. Plants require water for photosynthesis and the increased evapotranspiration, in comparison to impervious areas, produces cooling (Akbari et al. 2001, Georgi and Zafiriadis 2006, Bowler et al. 2010, Gunawardena et al. 2017). In addition, trees may provide shading thus preventing solar radiation from reaching and being absorbed by impervious surfaces where it may be stored and reradiated during the night (Upmanis et al. 1998). Analysis of land surface temperature (LST) as a function of vegetation (NDVI) has demonstrated that the more dense the vegetation (i.e. higher evapotranspiration) the greater the cooling (Eswar et al. 2016, Essa et al. 2017). Blue infrastructure has also been shown to have cooling impacts (Žuvela-Aloise et al. 2016). For these NBS, not only is there increased evaporation, but the water acts as a heat sink, and the more volume (i.e. greater depth per unit area) the better the heat is stored. In addition, if the water is flowing, it has the ability to transport the heat downstream and potentially out of the city.

Based on the studies above, NBS types which typically contain many large trees, such as botanical gardens, riparian and other woodlands were assigned the highest category of 'very high'. NBS types with fewer trees, such as parks and heritage gardens, and structures designed to provide shade like pergolas scored ‘high’. Street trees are typically smaller in size than woodland trees, often very small, and so provide less evapotranspirative cooling, but can still be important for shade; they were assigned a value of ‘medium’ to cover the range in size and stature of street trees. Roof gardens were assigned a ‘medium’ value due to medium to low-growing vegetation. The UHI effectiveness of green roofs varies with the type of green roof design. Intensive green roofs with a substrate layer more than 12 cm have higher vegetation and a higher level of evapotranspiration and insulation, but are still relatively rare, and can be considered analogous to roof gardens. By contrast, extensive green roofs with Sedum type vegetation on a thin substrate are typically chosen for residential and industrial buildings and provide less cooling than intensive or semi-intensive green roofs. Overall, we assign green roofs a ‘low’ score to represent the current level of implementation and choice of design (Besir and Cuce 2018). Grassy or shrubland areas were assigned a ‘low’ value due to lower evapotranspiration and no shading. Blue infrastructures were assigned a value depending on the water depth and whether the water was flowing or stationary, with deep or moving water like the sea, lakes or rives scoring ‘very high’ or ‘high’. Still or slow-moving water or shallower water bodies were generally scored ‘medium’. Surfaces which are predominantly un-vegetated, such as permeable paving were assigned ‘negligible’.

2.5.5 Water quality mitigation

As with air pollution removal, the level of benefit depends heavily on the pollutant involved. Urban water bodies of concern are surface water (wetlands, lakes and streams) and groundwater. For a holistic understanding of benefits it is important to take into account secondary processes, for example those determining eutrophication impacts. Secondary processes are important in streams and can result in considerable changes in impact downstream from the NBS. In addition those NBS and pollutant interactions affecting habitat will have a strong bearing on the ecological health of waterbodies. In terms of primary processes, the detention or permanent removal of pollutants in runoff or in infiltration to the sub-surface are the main pathways to water quality benefit. This assessment is restricted to consideration of the role of NBS to alleviate nutrient pollution and eutrophication impacts. Even so there are complex responses depending on whether or not pollutants are attached to particulates (e.g. phosphorus) and whether they occur in oxidised (e.g. nitrate) or reduced form (e.g. ammonium).

The benefits of woodland are equivocal and seasonally-controlled. Leaf litter plays an important role in water quality, and can act as a pollutant itself (Bratt et al. 2017). There is evidence that phosphorus inputs to water bodies are reduced by woodland but less clear evidence of nitrogen abatement (Brett et al. 2005, Nidzgorski and Hobbie 2016), therefore overall most forms of woodland are scored as ‘high’. However, riparian woodland provides ‘very high’ benefit, as it’s riparian location means it can intercept and buffer runoff as well as reducing algal growth by shading the river channel (Hutchins et al. 2010, Feld et al. 2018, Bachiller-Jareno et al. 2019). Similarly wetlands are long-known to be highly effective at improving water quality, and so score ‘very high’, although saturation effects and response non-linearities can occur (Larsen and Alp 2015). In-stream processing within rivers and other water bodies is less than that of lakes and in turn less than that of wetlands (Saunders and Kalff 2001) and is scored ‘medium’, apart from canals where the slow-moving water scores ‘low’. Of the infrastructure-designed features, attenuation ponds and permeable paving generally score ‘high’ (Liu et al. 2020), since they are designed to intercept water and filter pollutants, with attenuation ponds scoring ‘very high'. Green roofs score 'low' because although they provide some filtration benefit (Shafique et al. 2018), this function only applies to atmospherically deposited pollutants. Parks are scored 'high' since they combine grassy areas and trees with reasonable infiltration, while predominantly grassy areas score 'medium' since infiltration is typically lower than for parks due to more compacted ground and lack of tree roots. Growing areas such as allotments and city farms are scored 'negligible' because the soil disturbance, and often additional nutrient additions, associated with cultivation are often a source of nutrients rather than a sink.

2.5.6 Water flow management

A wide range of blue-green NBS technologies exist to combat the risks posed by flooding and the threat of increased frequency and severity of flooding posed by climate change. These technologies are widely applied, to varying degrees and at varying scales, in many urban centres around the world to provide some means of flood mitigation and adaptation (Jongman 2018).

This type of urban flood adaptation technology - generally termed Sustainable Drainage Systems (SuDS) in the UK, or Low Impact Development (LID) in the USA - is considered 'green' engineering that can have multiple related ecosystem service benefits and considerably reduce the use of non-sustainable materials and processes compared to traditional hard or 'grey' engineering and infrastructure. SuDS include a suite of measures based on variable hydrologic controls that reduce urban runoff through enhanced infiltration and localised retention of storm runoff (e.g. rain gardens, permeable paving, green roofs) or provide control for reducing storm runoff from surrounding impermeable surfaces or upstream developed areas through localised storage and attenuation of outflow (e.g. detention basins, swales, ponds). Although SuDS are primarily small scale, lakes and reservoirs can provide similar functions at larger scale. The overall concept of SuDS is to slow the flow of water through an urban system, using natural processes where possible, to retain rates of runoff in line with natural 'greenfield' runoff rates (Miller and Hutchins 2017). These technologies are well proven and widely adopted, and are scored as 'very high' or 'high'. For example, a review of 60 published green roof studies, conducted across tropical, arid, temperate and continental climates, showed an average annual retention of 60% of rainfall (Akther et al. 2018). Independently of retention, green roofs also temporarily detain rainfall, delaying its conversion to runoff (Stovin et al. 2012, Vesuviano et al. 2014).

While widely adopted for their role as urban NBS there is considerable uncertainty on the role of trees as urban NBS for flood mitigation. A review of 49 primary studies (Baker et al. 2021) found that a majority (27) reported that increasing tree cover decreases runoff, while some reported increased interception (17), evapotranspiration (7) and infiltration (6) losses. The water-flow management benefits of trees may be limited to water resources and reducing runoff in more routine events, rather than the extreme events that normally cause flooding. A systematic review of 71 studies (Stratford et al. 2017) focusing specifically on river flooding found that trees at a catchment scale play a larger role in reducing the more routine small floods, and that the majority of evidence is from modelling studies. In fact there are few empirical urban tree studies that are able to directly link trees to flood mitigation. On balance, reflecting this evidence, trees and shrubland are scored 'high', while parks and areas with a mix of tree and grass cover are scored 'medium'. Grassy areas are scored 'medium' or 'low' depending on how compacted they are, with highly managed or trampled soils having poor or limited infiltration capacity.

2.5.7 Carbon stocks

Here we consider the carbon stocks in each NBS type rather than annual sequestration rates for which there is far less information. We consider both above ground C and soil organic C (SOC) to support the assessment of relative ability of NBS types to hold C. Urban areas are difficult to sample, particularly for soils, due in part to private ownership of much of the city area, and existing studies have used a wide variety of sampling depths and approaches for soil measures (Lorenz and Lal 2015, Richter et al. 2020) which make comparisons of NBS types a challenge. In addition, many assessments are for sample points representing specific land cover types such as trees, shrubs and grass, making it difficult to extrapolate to complex features like gardens and parks.

Most studies show that trees hold large amounts of above-ground C relative to other land covers. For example, in parks in Auckland, New Zealand, trees store 64 times more C than shrubs (Wang and Gao 2020). For urban trees and woodlands, carbon storage depends on factors such as density of trees, tree species, height and age, with urban trees and especially street trees typically much smaller than rural trees. Estimates of carbon stock in urban forest, as well as the relative storage in above ground biomass and in soils therefore vary widely, in part due to climatic factors. In Harbin, China, urban trees store 77 t C ha-1 and SOC was 54 t C ha-1 (Lv et al. 2016) , while in Leicester in the UK, above ground biomass of urban trees was 280 t C ha-1 (Davies et al. 2011) and SOC was around 35 t C ha-1 (Edmondson et al. 2014). Meanwhile, in parks in Helsinki, Finland a study found that trees held 22 to 28 t C ha-1 and SOC was at least 104 t C ha-1 (Lindén et al. 2020).

A few studies have performed relatively comprehensive sampling of either above-ground biomass, SOC or both allowing some comparison of C stocks in urban NBS (Davies et al. 2011, Edmondson et al. 2014, Mexia et al. 2018, Richter et al. 2020). Based on these studies, trees and woodland were assigned ‘very high’, parks and areas with a moderate amount of tree cover, including cemeteries, scored ‘high’ while street trees and shrubby areas were generally assigned ‘medium’. Grassy areas were assigned ‘low’. Green roofs were also assigned ‘low’ but roof gardens were assigned ‘medium’ due to deeper soil substrates and the taller vegetation they can support. Predominantly sealed surfaces were assigned ‘negligible’ although several studies sampling under these surfaces have shown that buried soil carbon persists there and can be greater than in agricultural areas under continuous tillage (Edmondson et al. 2012).

Aquatic systems can store considerable amounts of C. The sea was assigned ‘very high’ due to large C stocks in coastal habitats such as saltmarsh and even intertidal mudflats (Beaumont et al. 2014). Most other aquatic habitats were assigned ‘medium’ as they store C in sediments, while rivers and canals were assigned ‘low’ as the ability to store C in these moving waters is more limited.

2.5.8 Biodiversity

The ability of NBS to support biodiversity is highly complex and it is difficult to summarise to a ‘per-unit’ factor since many other factors influence biodiversity. Three aspects to note are size, management, and connectivity (Evans et al. 2009). Among the same type of NBS in a city, larger sites, in general, can support a higher level of biodiversity than smaller sites. This is partly because larger sites will generally be more heterogenous and contain more diverse habitats and have greater structural complexity than smaller sites (Johnson and Handel 2016). For example, there were more bird species and a higher percentage of rare species in large parks than in smaller parks in Nanjing, China (Yang et al. 2020). In addition, larger areas of NBS have smaller influence of edge effects and more available habitat for territories (Beninde et al. 2015). Secondly, management is important, for example to keep parks visually 'tidy' often grass is cut frequently and dead wood and leaves are cleared away, reducing both structural diversity and the food and niches to support saprotrophic and other species (Lepczyk et al. 2017). Thirdly, because many species are highly mobile, the habitat quality within the surrounding area (i.e. size and diversity, and connectivity of greenspace) is extremely important (Braschler et al. 2020). Diversity across patches such as private gardens can support more species (Idohou et al. 2014, Van Helden et al. 2020), and woody plant species diversity in urban woodlands is influenced by the urbanization levels in surrounding environments (Yang et al. 2021).

Nonetheless, it is possible to establish a relative hierarchy of the ability of NBS to support biodiversity, and similar approaches have been used to develop simple metrics of urban biodiversity potential. NBS types with trees or woodland tend to be more structurally diverse than other NBS types and support higher biodiversity, particularly where native species are predominant. Thus, parks and cemeteries are scored 'high', and woodland as well as interface habitats, particularly between green and blue like riparian woodlands are scored 'very high'. Parks near water bodies supported more forest bird species than those without in Beijing, China (Xie et al. 2022). Street trees are scored 'medium' since they are more likely to be non-native species, and often of lower stature than trees in parks and woodlands. More managed environments such as home gardens, pocket parks are scored 'medium', while predominantly grassy areas including road verges are scored 'low'. Green roofs are also scored 'low' since the majority have very low structural complexity, while roof gardens are scored 'medium' to reflect their generally greater structural diversity. This sequence of decreasing diversity is supported by NBS types reviewed in Aronson et al. (2017).

For water-based NBS types riparian woodland can alter the structure of aquatic diatom communities (Smucker et al. 2013) and increase fish density and size (Kupilas et al. 2021), which all contribute to the 'very high' score for riparian woodland. Bluespace features like wetlands, rivers and ponds are scored 'high', while larger and generally more natural features like lakes, estuaries and the sea are scored 'very high'. More managed water-based NBS are given a lower score than their more natural equivalents, thus reservoirs are scored 'medium' and canals are scored 'low'.

2.5.9 Physical activity

Although the evidence is mixed, access to parks is associated with increased physical activity (Coombes et al. 2010, Schipperijn et al. 2017). Evidence from England suggests that urban parks are the most common place for both moderate and vigorous intensity physical activity (White et al. 2016), with woodlands and pathways (footpaths and multi-use trails) also being popular for moderately- and vigorously- intensive physical activity respectively. Overall, parks were scored 'very high'. However, pocket parks are used less for physical activity (Peschardt et al. 2012, Cohen et al. 2014), and were scored 'medium'; other forms of accessible green space, where there is less support for, or acceptability of, use of the space for physical activity, such as heritage parks and cemeteries, were either scored 'low' or 'medium'. Trails and footpaths are typically used for walking, running and cycling (Abildso et al. 2021, Hughey et al. 2021). As such, they support 'very high' levels of physical activity.

Sports fields, school yards and playgrounds were categorised as 'very high' as they facilitate many forms, and higher intensities, of physical activity (Rung et al. 2011). Use of these different spaces tends to vary with age (Flowers et al. 2019).

Garden use has been linked to individuals being more likely to meet physical activity guidelines (de Bell et al. 2020), and was scored 'very high'. The type of garden may influence the probability of use and whether physical activity is conducted. There is some suggestion that those with private gardens or access to private outdoor spaces are more likely to be sufficiently active for health, compared to those with communal gardens or no gardens (de Bell et al. 2020).

A systematic review concluded that there is a positive association between outdoor blue spaces and physical activity (Gascon et al. 2017). In England, coastal proximity is associated with more physical activity and more walking in particular (White et al. 2014, Elliott et al. 2018, Pasanen et al. 2019). The sea and other aquatic environments provide opportunities for swimming and watersports which are typically moderately intensive activities (Elliott et al. 2015), with the sea scored 'very high', lakes and reservoirs scored 'high', and other aquatic habitats scored 'medium' where the options for water-based activities were lower. Wetlands and ponds were scored 'low' and 'negligible' respectively, as they allow limited physical activity.

2.5.10 Social interactions

A number of NBS types provide opportunities for social interaction and forms of sociability that encourage social cohesion (Francis et al. 2012, Hartig et al. 2014). The ranking placed on these relates to the likely use of such spaces for intentional and unintentional interaction. For gardens, balconies are assumed to provide 'low' level of benefit, given they can be on different levels and so provide less opportunity for incidental interaction. Private gardens are given a 'medium' as they can offer both the potential for incidental and deliberate interaction – but in terms of overall impact they are considered to deliver less impact than communal gardens, which may offer space for interactions for many different users (de Bell et al. 2020), and are assigned a value of 'high'. Pocket parks and parks offer greater potential than communal gardens and are rated 'very high', given potential use by dog walkers, recreational users and for planned social activities (Seeland et al. 2009, Peschardt et al. 2012). Botanical and heritage gardens are rated 'high', because use may be restricted by the facilities or planting arrangements. For that reason, nursery gardens are rated 'medium'. Sports fields offer spaces for recreational activity with groups, but are rated 'high', rather than 'very high' as they tend to have fewer facilities that encourage social interaction, e.g. benches, and access for certain users may be restricted (e.g. dog walkers).

For other public spaces, the ratings are based on the general potential for social interaction – e.g. in cemeteries that are in operation, the space for walking or talking may be limited and there may be social taboos in certain countries for the use of such spaces for recreation. Conversely, some cities, including those in Scandinavia, are encouraging the use of cemeteries to capture multifunctional benefits (Grabalov and Nordh 2021). Allotments have been shown to contribute to social opportunities (Genter et al. 2015) and so are rated 'high'. City farms are considered to provide 'medium' opportunities for social interaction, though this is likely to vary with the type of farm in question – e.g. care farms which are designed for use for therapy may provide more social benefits (Hassink et al. 2010).

Different linear features may give different affordances for social interaction, and these may depend upon context. Street trees are considered to generally have 'low' benefit for social interaction – but these may be higher in hotter countries where trees provide shade in which people can sit and socialise (Mehta 2009). Cycle paths are considered as 'medium', given the potential for use by cycling groups and for incidental interaction with others en route. Footpaths are considered as 'very high' with many opportunities for interaction, the rise of social walking groups and their use in green prescriptions (Husk et al. 2020). Assuming public access, both riparian woodlands and woodlands are considered as 'high' (O'Brien et al. 2014). Hedges and road verges are assumed to have 'negligible' benefit for social interaction – indeed hedges may create a barrier to interaction.

In terms of constructed NBS, green roofs and green walls are assumed to be 'negligible', whilst roof gardens, if communal, may afford 'high' levels of social interaction, similar to communal garden spaces. Pergolas are assigned 'low', and can be considered similar to street trees, in that they provide shade - they may be more important in hotter areas. Hybrid GBS (see typology) for water are all assigned 'low' or 'negligible' as they have few design features aimed at encouraging human interaction.

Blue spaces, including rivers, lakes, and canals are rated 'high' with the sea (harbour areas, coasts and associated beach areas) rated as 'very high'. Spending time with family and friends was the second most commonly reported perceived benefit from visiting freshwater blue spaces in a survey sample of Great Britain (De Bell et al. 2017), and use of beaches may be particularly important for intergenerational play (Ashbullby et al. 2013, Elliott et al. 2018). Wetlands have comparatively limited social uses and are scored 'low'.

Shrubland and sparsely vegetated land are rated 'medium' since such spaces can be used for recreational groups (e.g. walkers, cyclists, bird watchers) and for picnic sites, while non-specified grassy areas are rated 'high', but not as much as formally delineated public spaces like grassy areas in parks which are more commonly recognised as gathering spaces.

2.5.11 Restoring capacities - stress reduction and cognitive restoration

Most NBS features were considered to provide opportunities for rest and relaxation, which can promote stress recovery and cognitive restoration (Hartig et al. 2014). Those with more diverse and 'natural' features were considered to deliver greater benefit (Annerstedt et al. 2012, Marselle et al. 2019). Therefore, botanical gardens and woodlands were scored 'very high' (White et al. 2013), while NBS with fewer natural features were scored lower. Scores also reflected their primary purpose, so cemeteries were scored 'very high', as well as for privacy, or lack of intrusion by other users. Thus, gardens as private spaces were scored 'very high' while shared or community gardens were scored 'medium'. Lower restorative potential was assigned to features that are typically used for other purposes or with characteristics that may detract from these psychological benefits (e.g. sports fields, playgrounds and schoolyards), so these were scored 'medium' White et al., (2013) found that feelings of restoration from visiting playing fields were significantly lower compared with open countryside. Similarly, restoration after everyday physical activity was found to be lower when conducted in outdoor built or highly managed environments (including sports fields) in comparison to natural settings (including forests and urban parks) (Pasanen et al. 2018]. We scored the potential for cycle tracks as 'high', consistent with footpaths, but we note that some cycle facilities, such as BMX tracks may have lower restorative potential. Roadside verges were scored 'low'. Allotments have also been found to provide an important space for stress relief {Genter, 2015 #2875). Similarly 'blue space' environments have been indicated as particularly beneficial in this domain (White et al. 2020), and experimental studies have indicated greater restorative potential of blue compared with green/grey spaces (White et al. 2010) so all were scored 'very high'. Psychological benefits were the most commonly reported perceived benefit from visiting freshwater blue space (De Bell et al. 2017).

2.6 Exploring synergies and trade-offs among NBS and the services they deliver

In order to assess the synergies and potential tradeoffs among different NBS in terms of the services they provide we conducted an ordination analysis. The assigned scores for service delivery were converted from ordinal scores to numeric ones ranging from 'negligible' = 0 to 'very high' = 4. Two inter-related assumptions are made: that all services are weighted equally, and that the highest level of benefit 'very high' has broadly equal magnitude for each service. We carried out principal components analysis based on a covariance matrix in Minitab v18.1. For the same ordination space, Figure 4 shows the relationship among NBS types, while Figure 5 shows the relationship among ecosystem services and wellbeing benefits provided. Thus, for interpretation purposes, the typology components found in the top left of Figure 4 will be mainly delivering the services found in the same top left space of Figure 5.

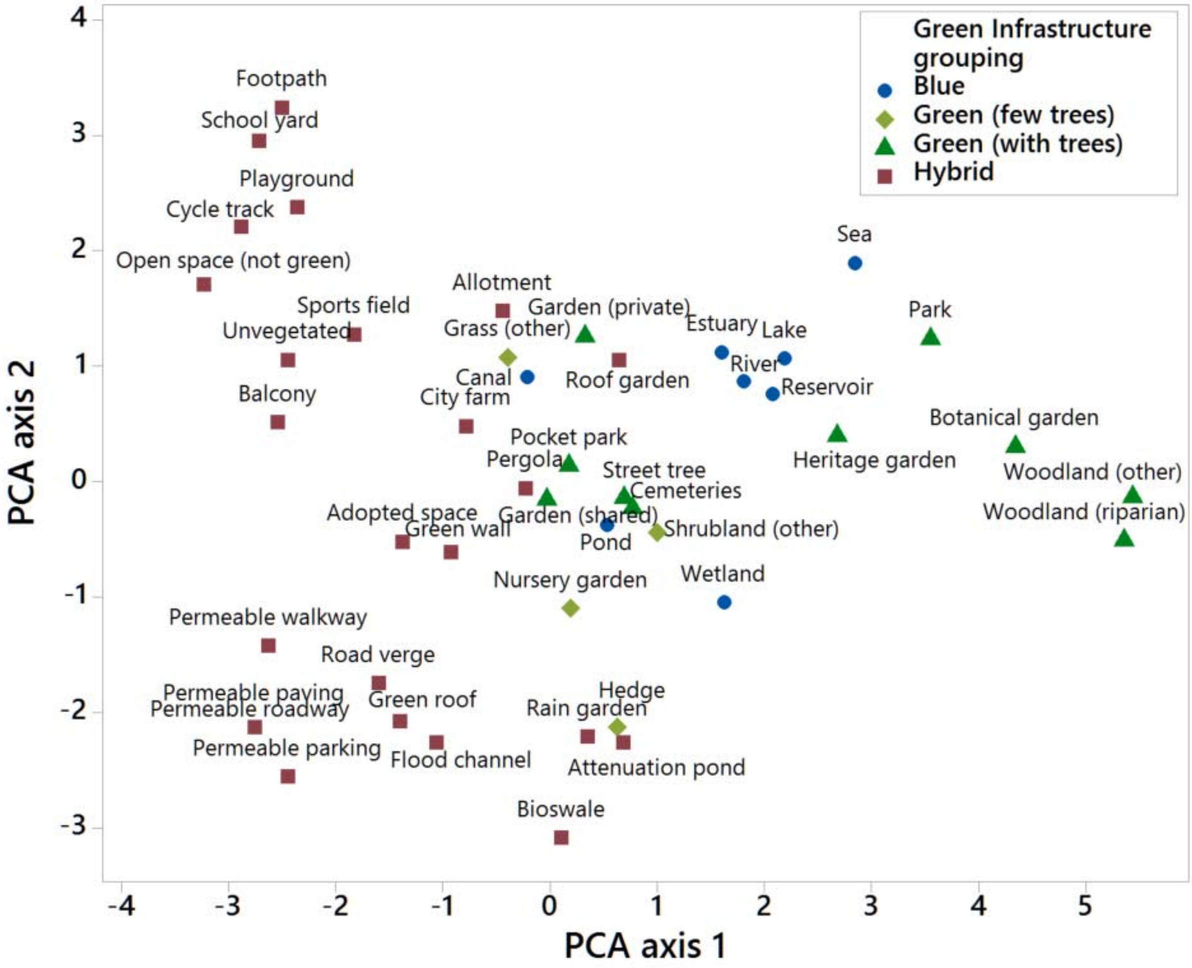

Figure 4: Principal components analysis showing relationships among NBS types.

In both diagrams, axis 1 reflects the degree of multi-functionality for a given NBS type, with NBS types that have high multifunctionality occurring on the right hand side of the diagram, while those which provide more of a single service or benefit on the left hand side of the diagram. Notably, axis 2 pulls out those NBS types which are more well-being focused, with those NBS types which deliver high wellbeing values located high on axis 2, and those NBS types which provide less wellbeing benefit located low on axis 2. A NBS strategy which aims to achieve maximum multiple benefits might therefore focus on NBS types which occur in the top right, so providing multiple benefits as well as high well-being, but strategies which aim to deliver particular outcomes, e.g. for a particular pressure such as flooding, or to maximise societal wellbeing will still select the NBS type that is most appropriate for that purpose.

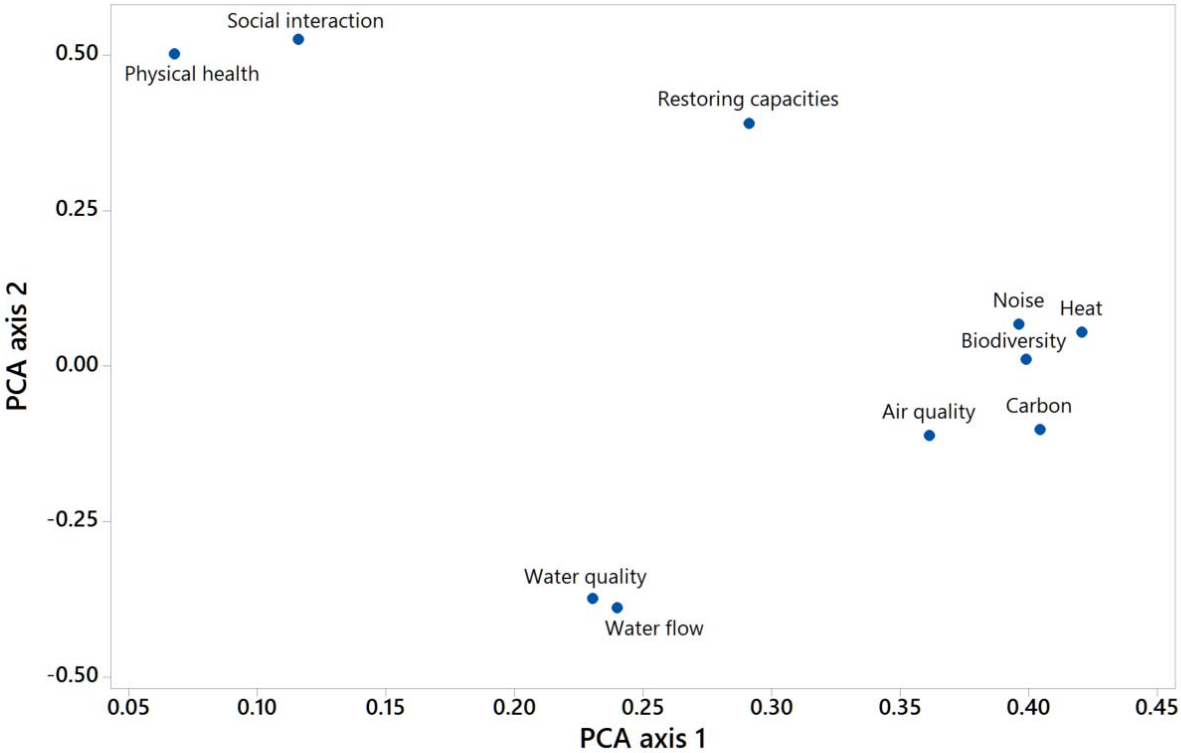

Figure 5: Relationships among ecosystem services and benefits, by principal components analysis.

2.7 Operationalising the framework

The typology and its associated ecosystem services benefit matrix can be used in different ways to support decision making. On its own, and in the absence of more specific data about use of green and blue space and the quantified services they provide, the matrix can be used as a first approximation of likely services provided for a given NBS type. This initial assessment of the relationships between NBS and the services they provide can also be used as the basis for detailed quantification of services to inform decision making, either through survey and data collection, or through modelling. In both cases, decision-making needs to integrate information about the potential service that can be provided with the specific desires and requirements of city residents, and following the principles of co-production to achieve consensus decisions. It is perhaps also a heuristic learning tool – as different contextual, spatial and temporal circumstances will lead to tweaking and developing the model as knowledge around these ecological and social functions improves.

2.7.1 Matrix of co-benefits for decision making

The ecosystem services benefit matrix can be used to plan and assess the multiple benefits likely to be achieved from a set of candidate NBS options. Direct use of the matrix is a suggested first approach where ecosystem service models are not readily available, or there are not the resources or time available to set them up. Filtering of the matrix based on prioritised outcomes will allow selection of those NBS which best suit the requirements of a planned NBS intervention in a particular location. The matrix also guides understanding of which multiple benefits are likely to be provided by each NBS type, which can help with better understanding and communicating the benefits of potential options in a decision-making context with stakeholders.

2.7.2 Ecosystem service modelling and assessment

The typology can also be used as the basis for ecosystem services modelling and assessment, and data collection on NBS performance. The more robust assessments of ecosystem services value come from surveys of users (for more wellbeing-focused assessments), from meta-analyses, or from biogeochemical and/or spatial models which are based on ecological functions. For example, water flow models such as SWMM (Bisht et al. 2016), air pollution removal modelling approaches (Nowak et al. 2018, Jones et al. 2019), or other urban-focused ecosystem services models such as InVEST carbon stock or cooling potential (Zawadzka et al. 2021).

This combination of data-driven approaches allows a more realistic assessment of the benefits that are provided by typology features in a specific land parcel or modelling domain. Initially, the information on relative performance of each typology element can be used to guide selection and parameterisation of features to include in a model. As the library of data and model results improves, it allows better quantification and further refinement of the performance of individual typology elements under different contexts.

2.7.3 Understanding trade-offs among services provided by NBS

The key trade-offs emerging between NBS types are those which are focused on particular services and which tend to have a large human capital component. In other words the more natural the NBS, in general the more multi-functional it is (Colléony and Shwartz 2019, Alves et al. 2020). Single focus NBS, particularly those designed around management of water flows (green roofs, permeable paving) are designed specifically to maximise a particular service outcome, but their limited multi-functionality should be borne in mind by urban decision-makers (Alves et al. 2020). This could perhaps be mitigated by considering additional NBS components in an integrated mix in the same location, where this is possible.

Trade-offs can also emerge in planning contexts, where the ideal solution is not possible. For instance, when aiming to address UHI effects in a densely built inner city, it will often not be feasible to change the landscape and implement a park or woodland, which would be the optimal solution. Here, street trees, green walls and green roofs may be the preferred option and provide some benefits, even if these, compared to woodland and water bodies, have a lower effectiveness. The choice of location of the NBS also matters for addressing specific challenges. To stay with the example of UHI, greening industrial rooftops, located in the periphery of a city, will not help address inner-city UHI, even if it is more feasible with the large flat roofs on typical industrial buildings. Meanwhile, synergies can also emerge through scale effects, creating additional positive outcomes. An example is the long-term policy and widespread implementation of green roofs in Basel, Switzerland, that have led to a novel presence of protected species under the Habitat Directive (Veerkamp et al. 2021), whereas a few green roofs would only have a low impact on biodiversity overall, as assigned in the matrix. The quality or design of an NBS also plays a central role in the level of service provided. For instance, by planting native species and a variety of species in urban areas, new plantings can benefit biodiversity as well as achieve other purposes.

The framework does not directly address dis-benefits. As examples, some trees can adversely affect human health because they emit large quantities of allergenic pollen, or emit biogenic volatile organic compounds which are a precursor for formation of secondary pollutants such as ozone (Calfapietra et al. 2013). Natural areas in an urban setting can support animals which carry ticks and human diseases (Grochowska et al. 2020), while NBS with water features may harbour insects such as mosquitos which carry disease or midges and other biting insects (Chaves et al. 2011). Conflicts between urban residents and wildlife such as deer, raccoons, and coyotes are another example of the inconvenient side of urban biodiversity (Soulsbury and White 2015). The framework could be adapted to include another dimension with scoring to characterise such dis-services. Ideally, both the benefits and dis-benefits would be incorporated into a modelling assessment which allows place-based characterisation of these factors to support decision making with context specific local data.

2.8 Conclusions

In this paper we have introduced a conceptualisation of NBS which at the core has the interaction between natural components and people, and an evidence-based assessment of NBS benefits. We discuss how the framework can be operationalised for decision-making. The expert-based matrix of ecosystem service benefits fills an important information gap. However, we fully acknowledge the limitation that while it is based on a sound understanding of ecological and social systems, further work is required to quantify the actual service delivery for each cell in the matrix. Of necessity, the assessment represents a simplification. In reality, the service delivered by a particular NBS will vary depending on factors such as the amount of pressure (heat, air pollution) and the size and characteristics of the local population who will benefit (Fletcher et al. 2021). Therefore, in addition to quantifying the amount of service, such quantification should also present information on the range and variation in the estimates of how much service is provided in different contexts.

Direct use of the NBS typology developed in this paper may be included in decision support when major urban challenges are to be addressed by policy interventions and by public-private initiatives. In these situations, the typology can provide crucial and specified input that in a systemic and multi-disciplinary perspective integrates the people, societal and bio-physical perspectives of the urban context. This integrated perspective offers a deeper understanding of the benefits – single or co-benefits – and suggests the potential disadvantages associated with urban NBS. The matrix also guides the different actors' understanding of which multiple benefits that are likely to be provided by each NBS type, and this overview and increased understanding can help better understanding and communicating the benefits of potential options in decision-making and implementation with stakeholders including citizens.

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ANNEX 1 – THE NBS – ECOSYSTEM SERVICE BENEFIT MATRIX

Brief description	Object type	Object category	Food provision	Air pollution removal	Noise mitigation	Heat mitigation	Water quality mitigation	Water flow management	Carbon stocks	Biodiversity	Physical activity	Social interactions	Restoring capacities - stress reduction and cognitive restoration
Mainly private space linked to dwellings	Gardens	Balcony	Low	Negligible	Negligible	Negligible	Negligible	Negligible	Negligible	Low	Negligible	Low	High
		Private garden	Medium	Low	Negligible	Medium	Medium	Medium	Low	High	Very high	Medium	Very high
		Shared common garden area	Medium	Low	Low	Medium	Medium	High	Low	Low	Medium	High	Medium
Mainly public space, but some access restrictions may apply	Parks	Pocket park	Low	Low	Low	Low	High	Medium	Low	Medium	Medium	Very high	High
		Park	Low	High	High	High	High	Medium	High	High	Very high	Very high	Very high
		Botanical garden	Low	High	Very high	Very high	High	Medium	High	Very high	Medium	High	Very high
		Heritage garden	Medium	Medium	High	High	High	Medium	Medium	High	Medium	High	Very high
		Nursery garden	Medium	Medium	Low	Low	High	Medium	Medium	Low	Low	Medium	Medium
Civic areas designed primarily for specific amenity uses	Amenity areas	Sports field	Negligible	Low	Low	Low	Low	Low	Low	Negligible	Very high	High	Medium
		School yard	Negligible	Negligible	Negligible	Negligible	Negligible	Negligible	Negligible	Negligible	Very high	Very high	High
		Playground	Negligible	Negligible	Negligible	Negligible	Low	Low	Negligible	Negligible	Very high	Very high	High
		Shared open space (not green)	Negligible	Negligible	Negligible	Negligible	Negligible	Negligible	Negligible	Negligible	Medium	Very high	Low
Mainly civic areas designed primarily for specific uses (not primarily leisure)	Other public space	Cemeteries	Negligible	Medium	Medium	Medium	Medium	Medium	High	High	Low	Low	Very high
		Allotment/shared urban growin	Very high	Medium	Low	Low	Negligible	Medium	Negligible	High	High	High	Very high
		City farm	Very high	Medium	Low	Low	Negligible	Medium	Negligible	Medium	Medium	Medium	High
		Adopted public space	Low	Medium	Low	Low	Low	Low	Negligible	Low	Negligible	Low	Medium
Linked to transport and access	Linear features/routes	Street tree	Low	High	Low	Medium	Low	Low	Medium	Medium	Negligible	Low	High
		Cycle track	Negligible	Negligible	Negligible	Negligible	Negligible	Negligible	Negligible	Negligible	Very high	Medium	Very high
		Footpaths, including along wate	Negligible	Negligible	Negligible	Negligible	Negligible	Negligible	Negligible	Negligible	Very high	Very high	Very high
		Road verge	Low	Low	Low	Low	Medium	Medium	Low	Low	Negligible	Negligible	Low
		Riparian woodland	Low	Very high	Very high	Very high	Very high	High	Very high	Very high	High	High	Very high
		Hedges	Low	Medium	Low	Medium	High	High	Medium	Medium	Negligible	Negligible	Medium
Constructed green and blue space, added to infastructure	Constructed GBS on top of infrastructure	Green roof	Negligible	Low	Negligible	Low	Low	Very high	Low	Low	Negligible	Negligible	Low
		Green wall	Negligible	Medium	Medium	Low	Negligible	Low	Low	Low	Negligible	Negligible	Medium
		Roof garden	Medium	Medium	Low	Medium	Low	Low	Medium	Medium	Low	High	Very high
		Pergola	Negligible	Medium	Low	High	Low	Low	Medium	Low	Negligible	Low	High
Infrastructure designed to incorporate some GBS components	Hybrid GBS (for water)	Permeable paving	Negligible	Negligible	Negligible	Negligible	High	High	Negligible	Negligible	Low	Negligible	Negligible
		Permeable walkway	Negligible	Negligible	Negligible	Negligible	High	High	Negligible	Negligible	Medium	Low	Negligible
		Permeable roadway	Negligible	Negligible	Negligible	Negligible	High	High	Negligible	Negligible	Low	Negligible	Negligible
		Permeable parking	Negligible	Negligible	Negligible	Negligible	High	High	Low	Negligible	Negligible	Negligible	Negligible
		Attenuation pond	Negligible	Low	Low	Low	Very high	Very high	Medium	High	Negligible	Low	Medium
		Flood control channel	Negligible	Low	Negligible	Low	Low	Very high	Low	Medium	Negligible	Low	Negligible
		Rain garden	Low	Medium	Negligible	Low	High	High	Medium	Medium	Negligible	Negligible	High
		Bioswale	Negligible	Medium	Low	Low	Medium	Very high	Medium	Medium	Negligible	Negligible	Low
Bluespace features	Wetlands	Wetland	Negligible	Medium	Low	Medium	Very high	Very high	Medium	High	Medium	Medium	Very high
		River/stream	Low	Low	High	High	Medium	High	Low	High	High	High	Very high
		Canal	Low	Low	Low	Medium	Low	Medium	Low	Low	High	High	Very high
		Pond	Negligible	Low	Low	Low	Medium	High	Medium	High	Low	High	Very high
		Lake	Medium	Low	Medium	High	High	High	Medium	Very high	High	High	Very high
		Reservoir	Low	Low	Medium	High	High	Very high	Medium	High	High	High	Very high
		Estuary/tidal river	High	Low	Medium	High	High	N/A	Medium	Very high	High	High	Very high
		Sea (+ coast)	High	Low	Medium	Very high	High	N/A	Very high	Very high	Very high	Very high	Very high
Other un-sealed features without specified use, often on private land	Other non-sealed urban areas	Woodland (other)	Low	Very high	Very high	Very high	High	High	Very high	Very high	High	High	Very high
		Grass (other)	Low	Low	Low	Low	Medium	Medium	Low	Medium	Very high	High	Medium
		Shrubland (other)	Low	Medium	Low	Low	High	High	Medium	High	Medium	Medium	High
		Sparsely vegetated land	Negligible	Negligible	Low	Negligible	Low	Low	Negligible	Low	Medium	Medium	Medium