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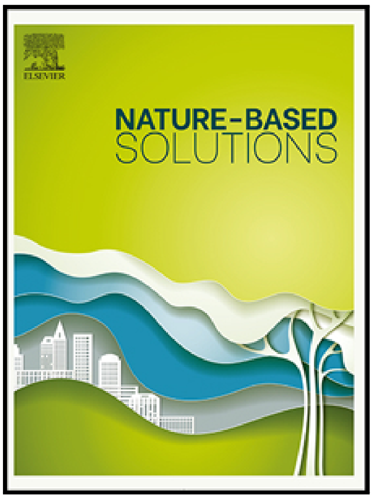

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A typology for urban Green Infrastructure, to guide multifunctional planning of nature-based solutions

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NBS Impacts and Implications

- We present a hierarchical, feature-based typology of urban GI which supports both mapping and modelling purposes.
- We synthesise the evidence behind the performance of each GI in addressing key services relating to environmental and social functions, including wellbeing.
- Analysis separates out a suite of GI ranging from low to high multi-functionality for regulating services, and low to high scores for cultural services. Multi-functional GI typically support higher levels of biodiversity.
- The multi-functional performance matrix can help design and plan new NBS in cities.

Abstract

Urban Green Infrastructure (GI) provides multiple benefits to city inhabitants and can be an important component in nature-based solutions (NBS), but the ecosystem services that underpin those benefits are inconsistently quantified in the literature. There remain substantial knowledge gaps about the level of service supported by less studied GI types, e.g. cemeteries, or less-studied ecosystem services, e.g. noise mitigation. Decision-makers and planners in cities often face conflicting or incomplete information on the effectiveness of GI, particularly on their ability to provide a suite of co-benefits. Here, we describe a feature-based typology of GI which combines elements of land cover, land use and both ecological and social function. It is consistent with user requirements on mapping, and with the needs of models which can conduct more detailed ecosystem service assessments which can guide NBS design. We provide an evidence synthesis based on published literature, which scores the ability of each GI type to deliver a suite of ecosystem services. In the multivariate analysis of the typology scores, the main axis of variation differentiates between constructed (or hybrid) GI types designed primarily for water flow management (delivering relatively few services) and more natural green GI with trees, or blue GI such as lakes and the sea, which deliver a more multi-functional set of regulating services. The most multi-functional GI on this axis also score highest for biodiversity. The second element of variation separates those GI which support very few cultural services and those which score highly in enabling physical wellbeing and social interaction and, to a lesser extent, restoring capacities. Together the typology and multi-functionality matrix provide a much needed assessment for less studied GI types, and allow planners and decision-makers to make *a-priori* assessments of the relative ability of different GI as part of NBS to address urban challenges.

Keywords

green and blue space; cities; ecosystem services; cultural services; wellbeing

1. Introduction

Cities are complex systems which encapsulate highly inter-connected and overlapping domains of built infrastructure and natural green and blue space components. Interfacing all of this are the people who live and work there (Jones et al. in press). The (semi-)natural spaces in cities 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. They have been defined in many different ways (Taylor and Hochuli 2017), but we term these collectively as Green Infrastructure (GI) in this paper. GI supports or enables multiple co-benefits to city residents and visitors through the ecosystem services it provides, as well as supporting biodiversity. These services include production of food, reduction of potentially harmful exposures (air and noise pollution mitigation, urban heat island reduction, flood mitigation), and cultural services (opportunities for physical activity, social interaction, and spaces for relaxation) (Tzoulas et al. 2007, Markevych et al. 2017), which in turn improve health and wellbeing (Chen et al. 2019). GI components are increasingly being promoted as 'nature-based solutions' (NBS) (Skodra et al. 2021) as a tool to address multiple interacting social and environmental challenges. NBS should promote biodiversity and involve active protection, management or creation of GI (Cohen-Shacham et al. 2016).

Many planning decisions are initiated in response to single-issue problems, such as surface flooding, poor air quality, or high air temperature during heatwaves. Lessons from complexity science are only slowly taken up in an urban health and well-being context (Gatzweiler et al. 2017). One of the strengths of GI above the standard technical built infrastructure solutions to urban problems, and a central aim of NBS, is that they are multi-functional (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, provide shelter and food for insects and birds, and support health and wellbeing of city residents. Therefore, understanding which set of services a particular type of GI provides can give urban policy-makers and planners more opportunity to design interventions around specific problems, and to choose the locations for implementation that are best able to address problems faced by urban citizens. Many assessments which quantify the performance of urban GI, tend to focus on single topics or features, such as green roofs (Manso et al. 2021), and do not collate the performance of a wide range of GI types. In their set of mini-reviews Keeler et al. (Keeler et al. 2019) focused largely on describing mechanisms and GI characteristics, and on social and structural constraints and contextual factors on the performance of GI rather than the effectiveness of specific GI types. There remains a lack of clear, collated information about the relative effectiveness of many types of GI to support a range of services. Further, there are substantial knowledge gaps about individual GI types which can only be filled at present by working from first principles and an understanding of the underlying ecological processes and social functions which they support. For example, the ecological and social functions that cemeteries provide are only recently being studied (Grabalov and Nordh 2021), but knowledge on aspects such as the degree of tree cover, sealed surfaces, public access in cemeteries can help evaluate which ecosystem services they provide, and to what level.

There are numerous typologies for GI, which tend to be derived from, or structured according to, available data. This includes satellite-based data processing, and/or publicly accessible mapping information (Koc et al. 2017) (Dennis et al. 2018). Approaches which rely on single-sources of data 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 GI 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 in a pocket park. These features are often essential to understand and quantify some of the functions that the GI can deliver such as carbon storage or air pollution removal. Typologies that combine elements of land use as well as land cover are the most useful, since both are necessary to determine the combination of ecological and social functions that GI provide, and their impacts on the well-being of urban residents (De la Barrera et al. 2016a). For example, riparian woodland will provide different levels of ecosystem service due to its location compared with woodland inside a park, or trees alongside a road. Ideally, a typology should be internally consistent, be able to address aspects of both ecological functions and human use, and be compatible with modelling approaches to calculate ecosystem services and benefits.

The objective of this paper is to introduce an internally consistent typology of GI, and a summary of the evidence base for the ecosystem services that each type of GI provides. In detail, we i) develop a feature-based typology for GI, ii) provide an evidence-based assessment of the ecosystem services that GI components provide in meeting particular urban-relevant challenges, and iii) illustrate how these services combine to deliver multi-functionality as a basis for use in implementing NBS. We conclude with recommendations on how to apply the framework in an urban planning context.

2. A feature-based GI typology

A typology based on GI features was selected as the most appropriate approach, rather than one based solely on land cover, or solely on public greenspace. This allows separate cross-matching of individual GI features with their ecological and social functions in order to provide a matrix of GI and ecosystem services. The typology was developed in discussion with experts from natural and social sciences, education and economics, and city officials from three European cities: Paris – France, Aarhus – Denmark and Velika Gorica - Croatia.

The typology (Table 1) combines aspects of land use and land cover. Thus, the components include discrete features such as gardens and parks which are typically managed as whole units but incorporate a range of land cover classes (trees, grass, water bodies, etc.), as well as land cover types such as woodland or grassland occurring in other urban spaces, both public and private. 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 47 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 include examples which are publicly accessible as well as examples which are privately owned and not accessible. Land ownership can severely restrict public access to many benefits provided by urban GI, particularly in urban areas where space is under high demand and parcels of land tend 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 could be received by different groups in society in particular locations (Nesbitt et al. 2018). For example, a communal garden area within a gated housing development would provide physical health benefits for private residents exercising in that garden. However, a range of other benefits are still provided to those who can't access it, including indirect benefits (e.g. from the air pollution removal that the garden provides) and some incidental benefits where the garden is visible from other locations (lowered stress levels as a result of seeing trees in blossom over the wall) (de la Barrera et al. 2016b).

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.

Table 1. Components and descriptions of the main and sub-classes of the typology.

Object type *(& description)*	**Object category**
Gardens *(Mainly private space linked to dwellings)*	Balcony
	Private garden
	Shared common garden area
Parks *(Mainly public space, but some access restrictions may apply)*	Pocket park
	Park
	Botanical garden
	Heritage garden
	Nursery garden
Amenity areas *(Areas designed primarily for specific amenity uses)*	Sports field
	School yard
	Playground
	Golf course
	Shared open space (e.g. square)
Other public space *(Areas designed primarily for specific uses (not leisure); some access restrictions may apply)*	Cemetery
	Allotment/other growing space
	City farm
	Adopted public space
Linear features/routes *(Linked to routeways, geographical features and boundaries)*	Street tree
	Cycle track (as part of blue/green corridor)

	Footpath (as part of blue/green corridor)
	Road verge
	Railway corridor
	Riparian woodland
	Hedge
Constructed GI on infrastructure *(Constructed green and blue space, added to infrastructure)*	Green roof (extensive)
	Green wall
	Roof garden (intensive)
	Pergola (with plants)
Hybrid GI for water *(Infrastructure designed to incorporate some GI components)*	Permeable paving
	Permeable parking/roadway
	Attenuation pond
	Flood control channel
	Rain garden
	Bioswale
Water bodies *(Bluespace features)*	Wetland
	River/stream
	Canal
	Pond
	Lake
	Reservoir
	Estuary/tidal river
	Sea (incl. coast)
Other non-sealed urban areas	Woodland (other)

(*Other un-sealed features without specified use, often on private land*)	Grass (other)
	Shrubland (other)
	Sparsely vegetated land

3. Ecosystem services provided by typology components

We created a matrix of potential delivery of a set of key ecosystem services in urban areas against all GI components in the typology. The ecosystem services span a range of provisioning services (food provision), regulating services (maintenance of carbon stocks, mitigation of poor air quality, noise, heat, water quality, flooding), and cultural services linked to delivery of physical and mental wellbeing (providing opportunities for physical health, social interaction, restoring capacities), as well as the potential to support biodiversity. The cultural services are broadly based on CICES definitions (e.g. physical and experiential interactions) (Haines-Young and Potschin 2018), but recognise the much wider literature which has recently emerged about the health benefits of urban GI, e.g. (White et al. 2016, van den Bosch and Ode Sang 2017). Benefits for educational purposes are not considered here, but are an important knowledge gap to be considered in future studies. The synthesis of literature focuses on exemplar studies which provide information on individual GI types, often drawing on existing review papers. The aim was to conduct a synthesis of the evidence rather than a systematic review, since this would have required a separate journal paper per topic. Each theme was led by experts from that discipline within the multi-disciplinary author team.

The assessment is based on the following principles. Ecosystem service delivery is considered as if it represented a quantity per unit area of the GI, e.g. per m^2. This allows direct comparability across different components. 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 typical types of GI found in temperate Western Europe, and may need to be adjusted for cities in other parts of the world, especially in different climatic zones or in 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 the published evidence of GI and ecosystem services. In order to fill in the gaps for less-studied GI components, it was necessary to work from first principles to extrapolate from an understanding of the basic underlying ecological, hydrological and social mechanisms involved. For example, although there are very few studies on cemeteries, it is possible to extrapolate their likely contribution to noise mitigation or to carbon sequestration from an understanding of their typical tree cover. For cultural services, 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 (Fitch et al. 2022), 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.

3.1 Food provision

GI in urban areas provides a range of opportunities for food production, ranging from cultivated areas to informal gathering of wild food. Formal food production in urban habitats occurs primarily in private gardens, city farms and community allotments. In some countries, food cultivation also takes place on vacant lands and in public parks. Some urban areas also contain areas of commercial agriculture, particularly where cities are rapidly expanding (Abd-Elmabod et al. 2019). 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 as GI and (extensive system) green roofs are scored 'negligible'. The more intensive 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).

3.2 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 NO_2 and SO_2 by plants occurs mainly by stomatal uptake, while removal of fine particulate matter such as $PM_{2.5}$ is dominated by dry deposition to surfaces (Janhäll 2015). From a health perspective, particulates and NO_2 are generally considered the most damaging in an urban context. The largest health benefits due to removal of urban pollutants by vegetation were associated with fine particulate matter ($PM_{2.5}$) (Jones et al. 2019), therefore this assessment focuses on mechanisms which remove $PM_{2.5}$, and on the resulting changes in pollutant concentrations, rather than the weight of pollutant removed. Dry deposition of $PM_{2.5}$ 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 GI types. Trees have a high leaf area index and roughness length and are more efficient at removing particulate matter than lower growing vegetation such as grass or other surfaces (Asner et al. 2003). Therefore GI 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 where these typically cover a moderate to low area overall. GI types made up of low growing vegetation, or with generally few trees, like gardens were assigned 'medium' while predominantly grassy areas and green roofs, footpaths, cycle paths and water bodies were assigned 'low'. Surfaces which are predominantly un-vegetated, such as permeable paving, were assigned 'negligible'.

3.3 Noise mitigation

GI 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 lead to the pressure level diminishing as the sound wave spreads out over a larger area. 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 compared with 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 GI that has the most substantial effect involves trees. Parks, large gardens and areas of woodland (including riparian trees and woodland along railway lines) will tend to provide the greatest level of mitigation, which is dependent on the density of trees and the depth of a tree belt 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 between the noise sources and the people.

3.4 Heat mitigation

Heat mitigation by GI 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 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 (typically with higher evapotranspiration per unit area) the greater the cooling (Eswar et al. 2016, Essa et al. 2017). Blue infrastructure also provides cooling (Žuvela-Aloise et al. 2016). For these GI types, 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, GI types which typically contain many large trees, such as botanical gardens, riparian and other woodlands were assigned the highest category of 'very high'. GI types with fewer trees, such as parks and heritage gardens, and structures with vegetation designed to provide shade like pergolas scored 'high'. Street trees are typically smaller in size than trees in parks or woodland, and so provide less evapotranspirative cooling, but can still be important for shade; they were assigned a value of 'high' 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 cooling 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, 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 and hedges, footpaths and cycle paths 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', with ponds scored 'low' due to their small size. Surfaces which are predominantly un-vegetated, such as permeable paving were assigned 'negligible'.

3.5 Water quality mitigation

As with air pollution removal, the level of benefit for water quality depends heavily on the pollutant involved. Urban water bodies of concern include 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 impact downstream from the GI. In terms of primary processes, the detention or removal of pollutants in runoff or in infiltration is the main pathway to water quality benefit. This assessment considers the role of any GI type which alleviates nutrient pollution and eutrophication impacts in water bodies. These responses can be complex, 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). Overall most forms of woodland are scored as 'high'. However, riparian woodland provides 'very high' benefit, as its 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 of nutrients and contaminants within lakes is lower than wetlands so they score ‘high’, while rivers are lower again, scoring ‘medium’ (Saunders and Kalff 2001) while canals and ponds with still or slow-moving water score ‘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 arable agriculture, 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. Golf courses are ‘negligible’ also due to fertiliser additions.

3.6 Water flow management

A wide range of blue and green GI technologies exist to combat the risks posed by flooding in many urban centres around the world (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 hydrological 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 (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), and are scored 'high'.

While widely adopted as urban GI, there is considerable uncertainty on the role of trees for flood mitigation. A review of 49 primary studies (Baker et al. 2021) found that a majority reported that increasing tree cover decreases runoff, however some reported increased interception, evapotranspiration and infiltration losses. The water-flow management benefits of trees may be limited to 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 role in reducing the more routine small floods, but may not reduce impacts of the largest floods. Furthermore, the majority of evidence is from modelling studies, and 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. Sealed surfaces are scored 'negligible'. The sea and estuaries are not scored because they are hydrologically downstream of cities. For this service they are a receiver of water rather than a GI feature which can regulate water flows (not-withstanding their potential role in causing flooding, which is not the focus of this paper).

3.7 Maintaining Carbon stocks

Here we consider the carbon stocks in each GI 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 this assessment of the relative ability of GI 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 GI 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 stock 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 - 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 across urban GI types (Davies et al. 2011, Edmondson et al. 2014, Mexia et al. 2018, Richter et al. 2020). Based on these comparison 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, including golf courses, 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.

3.8 Supporting physical activity

Although the evidence is mixed, access to parks is associated with increased physical activity (Coombes et al. 2010, Schipperijn et al. 2017). A study in England suggested 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), although 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' as they allow limited physical activity.

3.9 Supporting social interactions

A number of GI 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 scored '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 among the wider population, 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). Overall, cemeteries are scored 'low. 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).

Linear features may give different affordances for social interaction, depending on 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 (where doctors prescribe activity in natural settings as a therapy in place of, or in addition to, pharmaceutical treatments) (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 GI, 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 GI (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 are not as important as formally delineated public spaces like grassy areas in parks which are more commonly recognised as gathering spaces.

3.10 Restoring capacities - stress reduction and cognitive restoration

Most GI features were considered to provide opportunities for rest and relaxation, which can promote stress recovery and cognitive restoration (Hartig et al. 2014) and they afford culturally patterned sensory experiences and thus a 'cultural education of the senses' (MacDougall 1999). 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 GI with fewer natural features were scored lower. Scores also reflected their primary purpose, so cemeteries were scored 'very high', due to their privacy, and general 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), scored as 'very high'. 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).

3.11 Supporting biodiversity

The ability of GI to support biodiversity is highly complex and it is difficult to summarise to a 'per-unit' factor since different taxa may have highly contrasting requirements. Nonetheless, the literature suggests that three important characteristics of GI are size, management, and connectivity (Evans et al. 2009). Among the same type of GI in a city, larger sites, in general, can support a higher level of biodiversity than smaller sites. This is partly because larger sites tend to 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 GI 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).

Based on these principles, it is possible to establish a relative hierarchy of the ability of GI to support biodiversity, and similar approaches have been used to develop simple metrics of urban biodiversity potential (Schwarz et al. 2017). GI types with trees or woodland tend to be more structurally diverse than other GI types and support higher biodiversity, particularly where native species are predominant (Alberti and Wang 2022). 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 in GI types matches findings in Aronson et al. (2017).

For water-based GI 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. Blue GI 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’. Highly managed water-based GI are given a lower score than their more natural equivalents, thus reservoirs are scored ‘medium’ and canals are scored ‘low’.

4. Exploring multi-functionality among GI types

In order to assess the synergies and potential trade-offs among different GI in terms of the services they provide we conducted an ordination analysis, as follows. The assigned scores for service delivery were translated 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 1 shows the relationship among GI types, while Figure 2 shows the relationship among ecosystem services. Thus, for interpretation purposes, the typology components found in the top left of Figure 1 will be mainly delivering the services found in the same top left space of Figure 2.

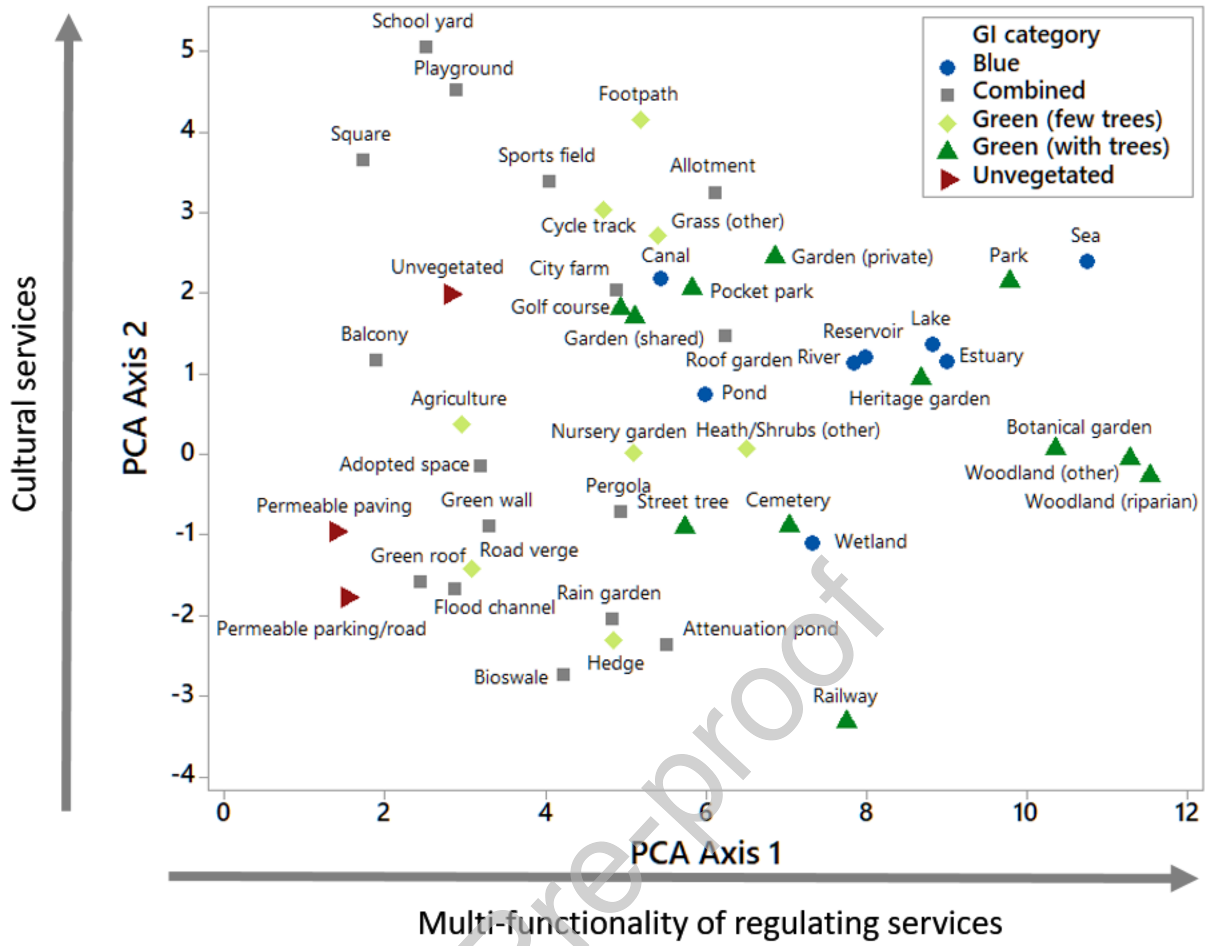

Figure 1. Principal components analysis showing relationships among GI types. Axis 1 represents increasing naturalness and multi-functionality of regulating ecosystem services, while axis 2 represents increasing potential to support cultural services. 'Combined' features (grey squares) have a large constructed element as well as green or blue elements.

In both diagrams, the dominant axis of variation, axis 1, reflects the degree of multi-functionality for regulating ecosystem services. GI types occurring on the right-hand side of the diagram have a higher level of multi-functionality, while those which provide more of a single service or benefit lie on the left-hand side of the diagram. Those with high multi-functionality for regulating services also tend to be more natural (green space with trees, large water bodies), and also score highest for supporting biodiversity. Axis 2 pulls out variation in the level of cultural services, with GI types delivering high levels of cultural services located high on axis 2, and those which provide lower levels located low on axis 2. A strategy which aims to achieve maximum multiple services might therefore focus on GI types which occur in the top right quadrant of the diagram, so providing multiple regulating services as well as high levels of cultural service. 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 GI type that is most appropriate for that purpose.

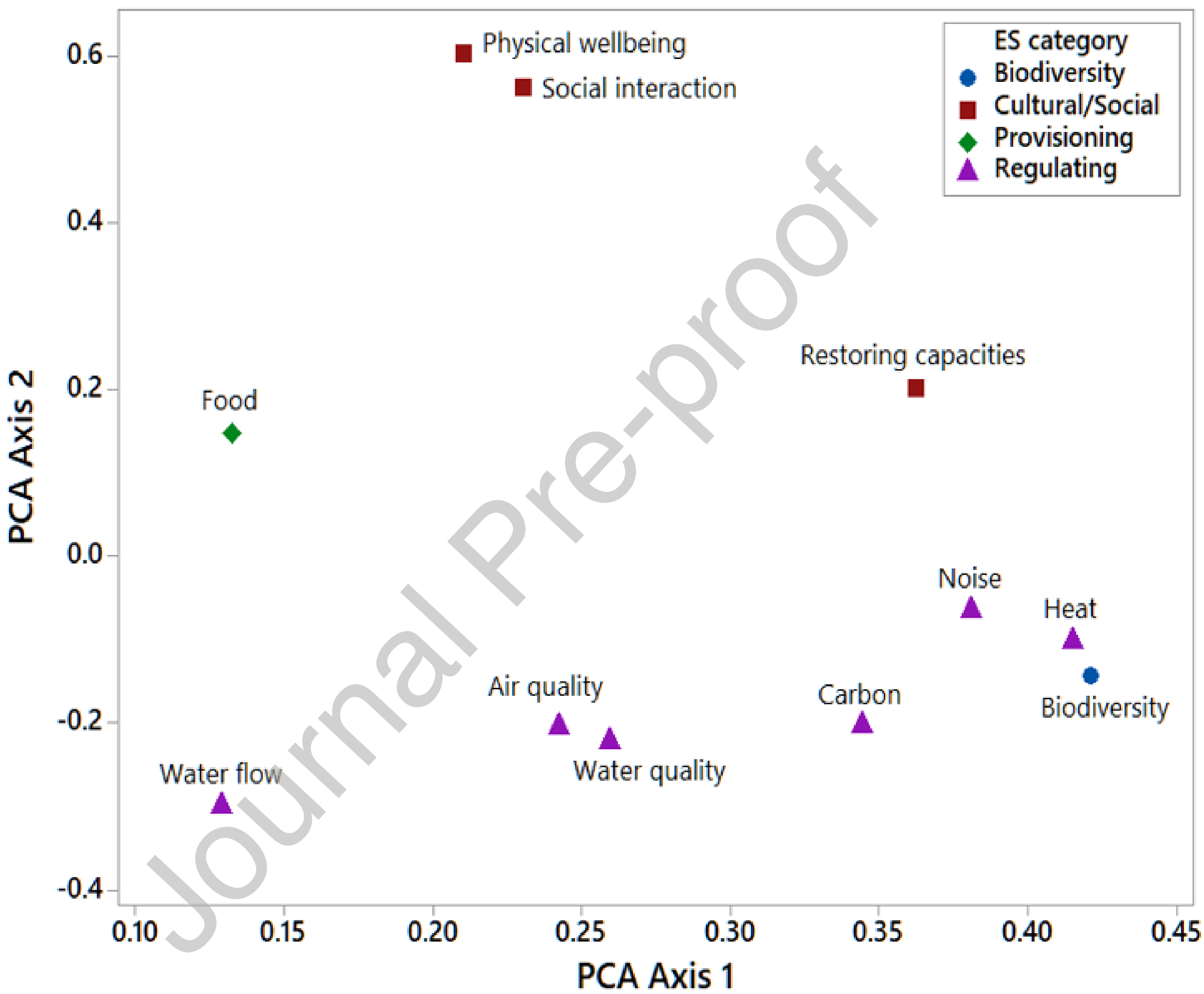

Figure 2. Relationships among ecosystem services, by principal components analysis. For interpretation of axes see Figure 1.

5. Operationalising the framework

The typology and its associated ecosystem services benefit matrix can be used in different ways to support decision making. In the absence of more specific data about the services that each GI feature can provide, particularly for less-studied types, the matrix can be used as a first approximation of likely services provided.

5.1 Matrix of co-benefits for decision making about NBS interventions

Where an NBS intervention is planned, the ecosystem services x GI 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 GI which best suit the requirements of a planned NBS intervention in a particular location. For example, if the greatest local challenge in a particular location is to reduce flood risk, then GI types which provide a high level of service to reduce water flows but also provide high levels of other co-benefits can be selected. Since the matrix clearly shows which multiple benefits are likely to be provided by each GI type, this can also help with communicating the benefits of potential options in a decision-making context with stakeholders.

5.2 Ecosystem service modelling and assessment

The typology can also be used as the basis for ecosystem services modelling and assessment, and data collection on GI performance. Robust assessments of the amount of ecosystem service provided can come from surveys of users (for more wellbeing-focused assessments), from meta-analyses of published literature, 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). The matrix is still useful for estimating co-benefits of GI types in an integrated assessment where models are not available for all services, or all GI types.

5.3 Understanding trade-offs and synergies among services provided by GI types

The key trade-offs emerging between GI 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 GI, in general the more multi-functional it is (Colléony and Shwartz 2019, Alves et al. 2020). Single focus GI, 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). To some extent this could be mitigated by considering additional GI 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 urban heat island 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 they have a lower cooling effectiveness when compared with woodland and water bodies. The choice of location for the GI also matters for addressing specific challenges. To stay with the example of cooling effects, greening industrial rooftops located in the periphery of a city, will not help address inner-city heat islands, 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 widespread implementation of green roofs in Basel, Switzerland, that has 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-services. As examples, some trees can adversely affect human health because they emit large quantities of allergenic pollen, or 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). While some of these dis-services relate to specific biodiversity elements, such as a particular species, they are still a relevant concern in decision making on urban NBS. 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.

6. Conclusions

In this paper we have introduced a typology of GI, and an evidence-based assessment of GI benefits, which together can inform NBS design for greater multifunctionality. 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, substantial 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 GI feature 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, attempts at quantification should also present information on the range and variation in the estimates of how much service is provided in different contexts.

The typology developed in this paper is useful for decision support when major urban challenges are to be addressed by policy interventions and by public-private initiatives. Here, the typology can provide crucial and specified input that 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 – associated with urban GI which can be used as the basis for designing and implementing multifunctional NBS, and can help in communicating the advantages of potential options to a range of stakeholders including the public.

CRediT statement

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Declaration of interests

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

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