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Airsheds, watersheds and more – The flows that drive intra-extra-urban connections, and their implications for nature-based solutions (NBS)

Laurence Jones[a,o,*], Stefan Reis[b,h], Mike Hutchins[c], James Miller[c], Baihuiqian He[b], Isabel Seifert-Dähnn[d], Chong-Yu Xu[e], Alex Hagen-Zanker[f], Jingyan Yu[f], Tao Lin[g], Haifeng Jia[i], Steven Loiselle[j], Duncan Russel[k], Clive E. Sabel[l,p], David Fletcher[a], Alice Fitch[a], Luis Inostroza[m,n,q]

[a] UK Centre for Ecology & Hydrology, Environment Centre Wales, Deiniol Road, Bangor LL57 2UW, UK
[b] UK Centre for Ecology & Hydrology, Bush Estate, Penicuik, EH26 0QB, UK
[c] UK Centre for Ecology & Hydrology, Maclean Building, Benson Lane, Crowmarsh Gifford, Wallingford, Oxfordshire, OX10 8BB, UK
[d] Norwegian Institute for Water Research, Økernveien 94, 0579 Oslo, Norway
[e] Department of Geosciences, University of Oslo, Oslo, Norway
[f] Department of Civil and Environmental Engineering, University of Surrey, Guildford GU2 7XH, UK
[g] Key Laboratory of Urban Environment and Health, Institute of Urban Environment, Chinese Academy of Sciences, Xiamen 361021, China
[h] University of Exeter Medical School, Knowledge Spa, Truro, TR1 3HD, United Kingdom
[i] Center for Urban Runoff Control & Stream Restoration, School of Environment, Tsinghua University, Beijing 100084 China
[j] Earthwatch Europe, Oxford OX2 7DE, UK
[k] Department of Politics, University of Exeter, Exeter EX4 4RJ, UK
[l] Dept of Public Health, Aarhus University, Aarhus 8000, Denmark
[m] Ruhr University Bochum, Institute of Geography, Universitätsstraße 150, Bochum 44801, Germany
[n] Universidad Autonoma de Chile, Av. Pedro de Valdivia 425, Providencia, Región Metropolitana, Chile
[o] Liverpool Hope University, Hope Park, Liverpool L16 9JD, UK
[p] Health Research Institute, University of Canberra, ACT 2601, Australia
[q] Mendel University in Brno, Faculty of Regional Development and International Studies, Zemědělská 1665/1 Brno, 613 00, Czech Republic

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ABSTRACT

Cities are highly complex, inter-connected social-ecological systems, encompassing social, built and natural/semi-natural components. They interact with their surrounding extra-urban areas at varying scales, from peri-urban and rural to global. Space is a valuable commodity in cities. However, in most instances, city planners tend to think about interventions only within cities and rarely about the wider connected domains outside. Yet, considering the wider spatial context, including space outside of the city boundaries, may open up opportunities to achieve substantially greater benefit for city residents without sacrificing valuable space, leading to more sustainable city design for people and the environment.

In this paper we discuss the intra-extra-urban flows which connect cities to their wider airsheds, watersheds, biosheds and resourcesheds, which in turn interact with their peoplesheds. For each domain, we illustrate the processes and the scales they operate at, and discuss the implications for optimum location of nature-based solutions (NBS) to address urban challenges. We suggest that integrating knowledge about these multiple sheds can inform holistic design of NBS to deliver greater benefit for city residents. This takes into account the synergies and multi-functional co-benefits which arise from a careful consideration of place and people, while minimising potential disbenefits and trade-offs.

> “It wasn’t a city, it was a *process*, a weight on the world which distorted the land for hundreds of miles around … Thousands and thousands of green acres were part of it, forests were part of it. It drew in and consumed … and gave back …”

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* Corresponding author at: UK Centre for Ecology & Hydrology, Bangor LL57 2UW, United Kingdom
E-mail addresses: LJ@ceh.ac.uk (L. Jones), Isabel.seifert@niva.no (I. Seifert-Dähnn), c.y.xu@geo.uio.no (C.-Y. Xu), tlin@iue.ac.cn (T. Lin).

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Terry Pratchett, Night Watch, p390.

“It takes a region to make a city”

Patrick Geddes

1. Introduction

Cities are highly complex systems, encompassing social, built and natural/semi-natural components [1]. Urban systems have dramatically changed during the last century, with cities acting as much larger hubs for people, economy and material fluxes, with a highly dynamic and multilevel connectivity that reaches the planetary scale. The pace of urbanization is fast producing a blurring of the traditional urban boundaries, both conceptually and operationally. Rates of urban expansion differ around the world [2] but the nature of cities is changing everywhere. This is the context in which city officials are making planning decisions. Arguably the most valuable commodity in a city is space, and using that space effectively is vital. Taking a wider perspective and considering biogeochemical and ecological processes as well as human interactions may indicate that the best place for an intervention to improve the lives of city residents could lie outside of the city jurisdiction, rather than inside the city itself. This does not negate the considerable importance of green and blue space within cities, but raises the idea that in some cases to achieve greater effectiveness, it would be better to consider interventions outside as well as inside city boundaries. Therefore, to improve the sustainability of cities going forward, we need to better understand how the city is embedded within its environment, and use this knowledge to inform optimum planning of interventions for city residents. This may require a fundamental shift in decision making around use of space both within the city and its wider spatial context.

There has been considerable focus on improving liveability through better use of green and blue space within and around cities [3]. Green and blue spaces have a broad definition, but are primarily ecological components within a city, which can vary from a single street tree or flowerbed to a large park or urban woodland, from a garden pond to rivers and the sea. They provide multiple benefits, and are a focus for nature based solutions (NBS), as a valuable tool to improve liveability for city residents. Here we define NBS broadly as interventions that address social, economic and environmental sustainability issues simultaneously, thereby presenting a multifunctional, solution-oriented approach [4]. Examples of benefits they provide include the cooling potential of green and blue space to reduce urban heat island effects [5], removal of air pollution by urban vegetation, and particularly trees [6,7], improvements in water quality and surface water flows in urban areas [8–10], and the contribution to physical and mental wellbeing [11,12]. In most instances, initiatives to use NBS for the benefit of urban residents consider these only within cities, such as planting of new street trees, better management of urban parks, and creation of green roofs [13]. However, cities do not exist in isolation but are highly interconnected in larger landscapes where complex reciprocal influences take place. The best place for some interventions to provide maximum benefit to city dwellers may in fact lie outside of the city.

The urban and surrounding areas are intimately linked, but the majority of research on NBS has been conducted at the scale of individual green space areas within a city [14], or has considered components of green space within an administrative boundary [15], which still contains non-urban land use. In studies of green space benefits it is still rare that the relationships between the urban area itself and its wider surroundings are considered [16]. Here we distinguish between intra- and extra-urban, where urban is defined as the morphological urban footprint for a city and intra-urban are the interactions that happen within that morphological boundary, while extra-urban has many elements ranging from the adjacent peri-urban fringe to areas clearly outside the city which incorporate rural areas (natural, semi-natural and agricultural) as well as other settlements.

The concept of the complex interactions of a city with its surroundings is not a new one, and is central to the ideas around Urban Metabolism [1,17,18]. However, understanding the spatial interactions from this multi-scale perspective is often overlooked by city authorities, planners, and those making decisions on how to manage our urban living space, particularly in the case of NBS. This may partly be because urban decision-makers have limited or no jurisdiction beyond the administrative boundary, creating a mis-match between administrative boundaries and interconnected natural systems whose boundaries often span several urban jurisdictions. Moreover, attempts to join up activities to reflect interconnected natural systems have been shown to be difficult because of unclear lines of accountability [19]. There is also a tendency to address problems at the location where they are apparent, which may not always be the most effective way to reduce impacts. For example, building higher flood defences when the better solution may be to address issues upstream in the catchment [20]. It is also the case that urban areas are often widely distributed in the landscape and exist as a form of continuum rather than always being focused into larger settlements or cities [21–23]. Yet, the role of administrative boundaries in driving decision making tends to consider ‘the city’ and ‘everywhere else’ as separate domains, and this viewpoint exerts a strong influence on how problems are solved. By contrast, an increased focus on NBS at wider spatial scales allows a more holistic view of addressing the many challenges facing cities, at a time when these challenges are being accentuated by climate change and rapid social change [24]. Together with an understanding of scale, recognition of the spatial domains that influence cities, how these domains interact and, consequently the potential trade-offs and synergies that come about from those interactions, can help determine optimum locations for NBS in a wider urban and extra-urban system.

Within greenspace research, there has been much focus on the size or area of greenspace in cities [25]. While there is now increasing recognition that the location of greenspace is also important [26,27], so far little attention has been paid to the scales at which different pressures operate and different benefits operate for beneficiaries in urban settings. Spatial context is important and requires an understanding of both the nature and scale of the pressure (air pollution, flooding), as well as the scale and reach of the NBS that might be used to mitigate that pressure [28]. Better understanding these aspects can help decide which is the best location for a particular intervention, whether that lies inside or outside the city, and what spatial configuration yields the best overall outcomes.

In one research area, hydrology, spatial dependencies are well understood [29]. To a large extent, fluvial flood risk is a function of activities happening in the catchment upstream of cities [30]. Likewise, water quality is affected downstream of cities by the activities taking place within the city itself [31]. In conceptualising how flows of the many components move across urban and peri-urban areas, it is useful to adapt ideas derived in part from an understanding of water movement within catchments or water sheds. In an urban context this thinking can be applied to flows of water, air, biodiversity, resources (including food, biomass, minerals, energy and waste), as well as people.

Therefore, in this paper we aim to explore the links between service flows within and between the intra-urban and the extra-urban (peri-urban, rural spaces and beyond) for a series of domains that are relevant to the design and management of NBS to optimise city liveability. This recognises explicitly that sometimes it may be better to manage natural areas outside of the city to improve quality of life within the city. We explore and provide examples for five key domains: water, air, biodiversity, resources , and people. In Section 2 for each domain we outline the key interchanges across urban and extra-urban areas including, where relevant, far-field effects, and show how a wider perspective can help better design NBS to solve urban challenges. In Sections 3 and 4 we discuss some interactions among these domains and how these can be brought together to inform new approaches for improved planning and location of NBS which take into account both spatial and temporal interactions, and the co-benefits which become apparent when looking across multiple domains. We conclude in Section 5 with a summary of the key implications of this approach for sustainable city management and provide proposals to influence future NBS policy within urban design and planning.

2. Multiple domains influencing cities

Cities interact with their surrounding areas in multiple ways, some of which are clearly recognised, such as watersheds, but many others less so. Here we describe the spatial reach of these interactions as 'sheds', broadly defined as the zones of influence where flows between cities and the surrounding areas have an identifiable effect on a city, for a given domain such as air, water, people, etc. Delineating these sheds provides opportunities to think about management of NBS in more holistic ways (Fig. 1). Sheds can exist across spatial scales, from the shed associated with a single tree at street level within the city, to rural, and extending to far-field – in many cases global - effects. It is important to stress that these sheds may include other settlements, and the interactions between cities may sometimes be greater than with rural areas. Unlike watersheds, other sheds are not always fixed in space but variable both in space and time, and can encompass both uni-directional (e.g. upstream and downstream impacts) and multi-directional influences. In this paper we focus primarily on the flows which occur between the city and surrounding areas, rather than those which occur within a city. The following sections explore these in more detail for five domains: water, air, biodiversity, resources, and people.

2.1. Water

Many of the concepts around spatial dependencies are well understood for water, but we briefly outline them here (illustrated schematically in Fig. 2), as a prelude to widening the concept to other domains. Flooding is treated separately from aspects related to water supply and water quality.

2.1.1. Flooding – upstream influences

Non-specialists tend to think of water movement within clearly defined surface-water catchments. However, the reality is less straightforward (Fig. 2). Surface-water and groundwater catchments are usually not spatially coincident. For surface water catchments, and the associated risk of fluvial (i.e. from rivers) urban flooding, upstream processes in headwaters greatly affect the degree of risk. This distal contribution to flood risk is especially apparent in cities with seemingly low risk of flooding from local factors but which lie downstream of areas of higher rainfall, steeper topography and impermeable bedrock, for example the city of York in north east England regularly floods as a result of heavy rainfall in upstream catchments [32]. For large rivers, this may occur hundreds or even thousands of km away, for example, the Chao Phraya river in Thailand [33] or the Meuse in Europe spanning three countries [34]. The entire surface water catchment is the area active in controlling fluvial flood risk for the city downstream. Groundwater flooding can also be a consequence of high rainfall infiltrating to the groundwater catchment outside the city, and discharging (returning to the surface) directly upwards from beneath the city but, as noted previously, groundwater catchments often differ from surface water catchments. Coastal cities may face additional risk from rising groundwater levels due to sea-level rise over longer time-frames [35]. Pluvial flood risk (from intense rainfall overwhelming drainage networks and natural infiltration) is often more localised within the city, but upstream processes in sub-catchments can also play a role. Water infrastructure like sewer systems receive upstream and surface drainage water, which can overwhelm the sewer capacity within an urban area.

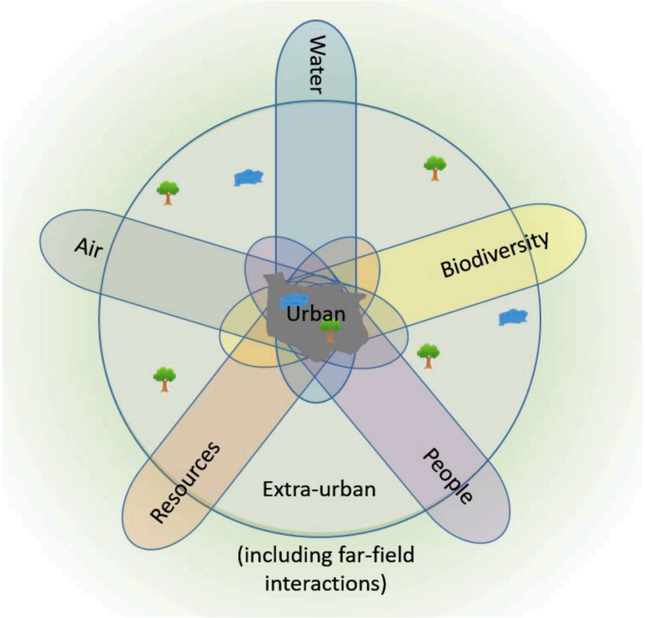

Fig. 1. 'Sheds' concept showing that urban areas interact with multiple domains, connected across scales.

2.1.2. Flooding - down-stream effects

The urban areas themselves can exacerbate flood risk in areas downstream through increased impervious cover and artificial drainage, which increases runoff and reduces hydrological response times [36]. This leads to more extreme 'flashy' flow regimes [37] and an increase in the frequency and magnitude of flooding downstream of cities [38]. This can have a large effect both locally and much further downstream if the urban area is relatively large compared to the downstream catchment.

2.1.3. Water supply and water quality – upstream influences and downstream effects

Additional relationships between urban areas and their surroundings apply when considering water supply and water quality. Water management systems dealing with both water demand and wastewater treatment are typically centralised within or across river basins. In large systems, individual cities may only represent a fraction of the total basin water demand, and a single resource (e.g. a reservoir) may provide for many cities and rural areas together and represent an integration of multiple water supply sources. Water supplies are typically stored in reservoirs upstream. In rapidly urbanising regions and nations, distal reservoir supplies are increasingly replacing local over-exploited resources [39]. Where water demand is high compared with local supply (for example due to size of city, or to climate), water provision may be from remote hydrologically-unconnected basins located in regions of greater resource [40]. Transfer of water between basins can be made direct *via* pipelines, or through canals joining existing river networks. For example, in China the Grand Canal transfers water over thousands of km from water-rich regions in the south to water-scarce urban and agricultural areas in the north, while in Southern Europe, the Tagus-Segura water transfer system diverts water from the Tagus headwaters to southeast Spain [41].

In decentralised systems, often prevalent in developing regions, water supply (e.g. small boreholes or reservoirs) and sewage treatment facilities (e.g. small works and septic tank systems) tend to be more localised, and may be specific to neighbourhoods. In such situations, local environmental conditions affecting availability (e.g. aquifer presence beneath a city) take on greater significance for service provision, as in Bangalore [42].

Upstream activities such as agriculture, industry and mining affect water quality in urban areas [43]. In turn, urban areas themselves impair water quality downstream, primarily through sewage, industrial

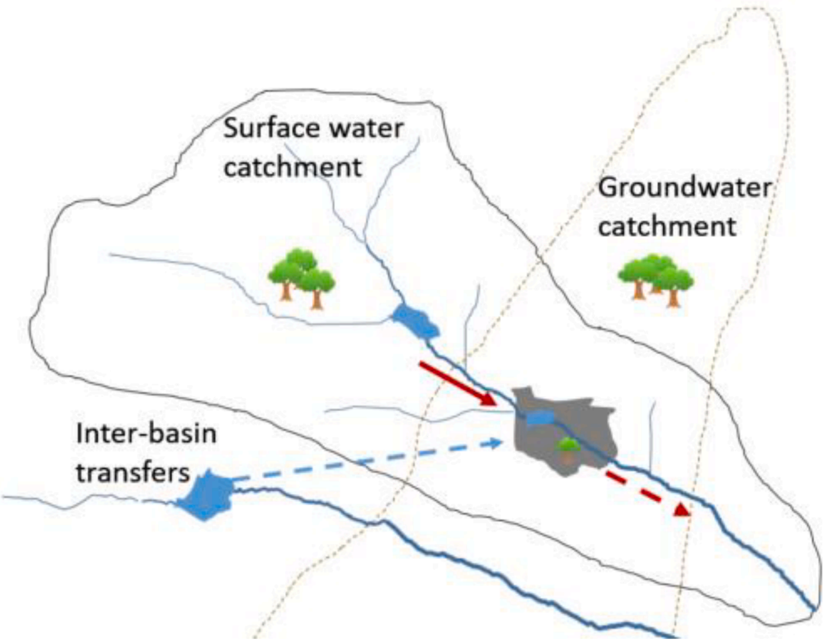

Fig. 2. Water sheds for surface water and groundwater influencing a city. Groundwater catchments may be different from surface water catchments. Trees indicate possible placement of NBS to mitigate water-based impacts.

effluent, road drainage, but also elevated water temperatures. The downstream water quality footprints of cities are large and predominantly defined by the level and type of centralised wastewater treatment, swamping the influence of diffuse runoff impacts on water quality in areas immediately downstream.

2.1.4. *Delineating watersheds*

Water sheds are likely to be different for each category (i.e. different for pluvial, fluvial and groundwater flooding, water quality, and water supply). In other words, there may be multiple watersheds for a single city. Watersheds are nested at multiple scales, with each water-course having its own sub-catchment. In addition, the functional watershed within an urban area may change over time due to man-made infrastructure, through artificial drainage, canals and water transfer schemes. Thus, the boundary and watershed will alter as drainage networks are updated or added for new developments, which effectively increases or decreases the catchment area [36].

2.1.5. *Implications for location of NBS to benefit cities - flooding*

Within a city, and acting mainly at a local scale, urban NBS for flood mitigation are provided by a suite of measures commonly termed Sustainable Urban Drainage Systems (SuDS) or Low Impact Development (LID) practices [44]. These have features that act to enhance local retention and infiltration of rainfall to reduce stormwater inputs into urban drainage and watercourses, thereby reducing peak discharges and flow volumes, and increasing flow lag-times [45]. Green Roofs have been shown to reduce surface runoff equivalent to 30% in significant events [46]. The use of local LID but implemented at scale over large areas is a key part of the 'Sponge-City' approach used in China. Modelling indicates that it can be relatively effective at increasing the volume capture ratio in large cities [47].

Taking a wider 'sheds' approach, upstream catchment management can be used to mitigate flooding in cities to some extent, using NBS instead of, or to supplement, dams and hard flood defences. Levers to achieve this, such as payments for ecosystem services, can incentivise land management practices which reduce downstream flood risk or improve water supply and quality [48–50]. Natural Flood Management activity such as restoring peatlands, river channels and floodplains, establishment of woodland, and encouraging natural waterlogging to detain runoff can reduce the height or timings of flood peaks in downstream cities [51,52], but may not mitigate the highest flow events [53]. Large-scale implementation of Sponge-City approaches can reduce and attenuate peak flows immediately downstream, reducing the chance of out-of-bank flows and exceedance of flood defences. However, this requires a relatively high proportion of SuDS to have observable impacts and model data suggest SuDS would not be effective in the most extreme events [54]. The beneficial effects show distance-decay, and decline further downstream once the catchment become less urbanised.

2.1.6. *Implications for location of NBS to benefit cities - Water quality*

Both within and outside cities, the benefits for water quality depend on wider catchment processes [43]. Within, and close upstream and downstream of cities, establishing tree canopy cover along river corridors and in riparian settings can reduce contaminants entering waterways, and can help mitigate some impacts in water bodies by shading and cooling the water which in turn reduces undesirable algal growth. At wider catchment scales, most city drinking water comes from supplies outside the city and riparian woodland in those catchments can help avoid contamination at source.

2.2. *Air*

2.2.1. *Upwind influences*

In a similar way to water, air masses (including the pollution they may carry) move across the landscapes forming an 'airshed' [55]. The upwind airshed (Fig. 3) reflects the zone of direct emissions of pollutants which affect air quality in the city. This includes precursor compounds such as ammonia and nitrogen oxides which are converted through chemical transformations in the air and contribute to the formation of secondary pollutants such as fine particular matter ($PM_{2.5}$) or ground level ozone. The airshed for a city can be more broadly defined as the area which influences atmospheric composition in a city by more than a certain percentage (or the area which it subsequently influences). Airsheds can be highly variable in size, depending on the pollutant type and weather patterns. Some pollutants are mainly active at a very local scale. For example, nitric oxide (NO) is very short-lived in urban areas and

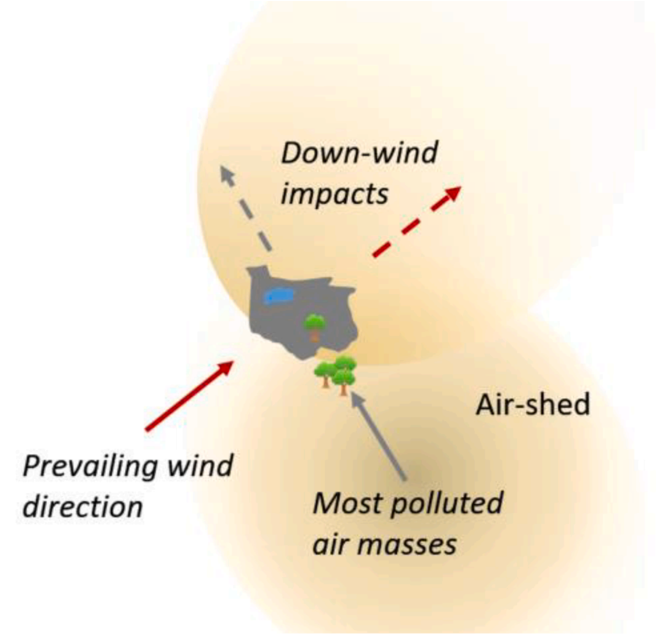

Fig. 3. Illustration of up-wind and down-wind influences which together define an operational air-shed for a city. Trees denote possible locations for NBS to mitigate impacts.

undergoes complex chemical interactions within a distance of tens of metres from its main source, road traffic, converting to NO_2 [56]. In an urban and extra-urban context, a large proportion of fine particulate matter ($PM_{2.5}$) in European cities is derived from precursor chemicals emitted in areas outside of the city [57], primarily from emissions of agricultural ammonia which forms aerosols of ammonium sulphate and ammonium nitrate [58,59]. Upwind air sheds can be global in some instances. Smoke particles from forest fires in Russia in 2004 travelled around the northern hemisphere in 17 days [60]. Similarly tropospheric ozone is seen as a hemispheric pollutant since many of its precursor chemicals are transported thousands of km around the globe [61]. While this description focuses primarily on atmospheric pollutants, the air shed concept applies equally to other compounds and particles mediated by atmospheric transport, including greenhouse gases such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), pollen and other substances, as well as waste heat or heat generated or stored within built surfaces as part of the urban heat island.

2.2.2. Downwind effects

There are also downwind effects in airsheds, which can be considered analogous to the atmospheric footprint of a city. Emissions within the city of pollutants from traffic, industry and residential areas contribute to the pollution plumes travelling downwind, and cities are mainly a source rather than a sink of gaseous pollutants [62]. These effects may occur in a wider direction to those of the upwind air shed since they combine the legacy of pollution transport from upwind with emissions occurring within the city itself (Fig. 3). Precursor chemicals for ozone formation are mainly emitted from urban sources, but ozone is primarily considered a rural pollutant. This is because within urban areas, photochemical reactions with other pollutants such as NO lead to destruction of ozone [63]. Thus, ozone concentrations are typically higher downwind of cities, but are relatively low in the cities themselves [64]. The temporal dynamics of pollutants may be influenced by weekday/weekend traffic patterns, or seasonal effects [65,66], as well as by wind direction. Such downwind effects can be persistent over timescales of decades to centuries. Pollutants from cities during the industrial revolution in the UK in the 19th Century have led to substantial accumulated sulphur in some rural areas downwind, such as the peatlands of the Peak District [67].

2.2.3. Delineating airsheds

Unlike water catchments, airsheds are spatially and temporally variable, depending on prevailing weather conditions, including the sources of short-range and long-range pollutants and precursor chemicals, seasonality and meteorology [64]. Therefore short time periods when particular wind direction and other meteorological conditions occur may be responsible for the majority of the pollution load [68].

Air sheds are loosely defined, but they can be quantified, either for individual events, by season, or as an annual or longer term average. Trajectory modelling of air masses, using lagrangian models can show flow paths from sources to destinations [69]. Over time, these can be used to build up a picture of the dimensions of the upwind airshed. Constructing a pollution rose, a form of wind rose which takes account of pollutant concentrations from each wind direction, better illustrates which wind directions transport the most pollution and indicates both the likely upwind air shed and downwind direction of effects. Fig. 4 illustrates this for a pollution monitoring location in the suburban area south-east of Birmingham, UK. It shows that although the prevailing wind direction is from the south west, these winds are relatively clean and the greater pollution loads (higher $PM_{2.5}$ concentrations) come from the East. The pollution rose also illustrates variability in the direction and magnitude of pollution concentrations across years, which is partly due to inter-annual variation in meteorology and the influence of longer-range transport of pollutants in different air masses.

2.2.4. Implications for location of NBS to benefit cities - Air quality

At local scale (tens to hundreds of metres), the quantity of air pollution removed by NBS such as trees tends not to make a difference to pollutant concentrations [70]. At this scale, they primarily act as barriers to trap or redistribute pollutants [71,72]. However, at larger scale woodland can reduce pollution concentrations such as $PM_{2.5}$ by a sufficient amount to result in aggregate benefits for human health [7,73,74]. Within a city it is difficult to scale up to sufficient area to achieve large reductions in pollutant concentrations [74]. Therefore, considering the larger scale of air sheds, there is substantial opportunity to reduce air pollutant concentrations passing into cities by locating woodland outside or on the edge of cities to supplement any within-city tree planting initiatives. In China, one solution to reduce long-range transport of dust has been to tackle the problem at source. The 'Grain to Green' initiative has planted trees and has revegetated desertified areas thousands of kilometres upwind [75], thereby reducing long-range dust pollution affecting Beijing. Solutions can be applied at multiple scales. For example, in addition to the Grain to Green initiative, China has planted forest around Beijing to intercept long-range pollutant transport as well as large scale planting within the city to reduce local impacts [76].

2.3. Biodiversity

2.3.1. Spatial influences

Species interactions with cities are not usually directional in the same way as air and water, but may operate from rural to urban and vice versa, including via waterways. Green and blue corridors, and connectivity between patches can add directional elements to species movements. Cities can offer a number of advantages for species adaptable enough to take advantage of them and overcome other hazards associated with urban areas. These advantages include availability of food or shelter, and reduced abundance of predators [77]. The structural and species diversity of plants, together with waterways, typically form the underpinning ecological habitats which allow these spatial interactions. The nature and timings of the movements are species dependent, summarised in Fig. 5. Some species find that urban areas provide high quality resting or roosting areas, such as the 0.75-1.5 million bats, roosting under the Ann W Richards bridge in Austin, Texas, which then

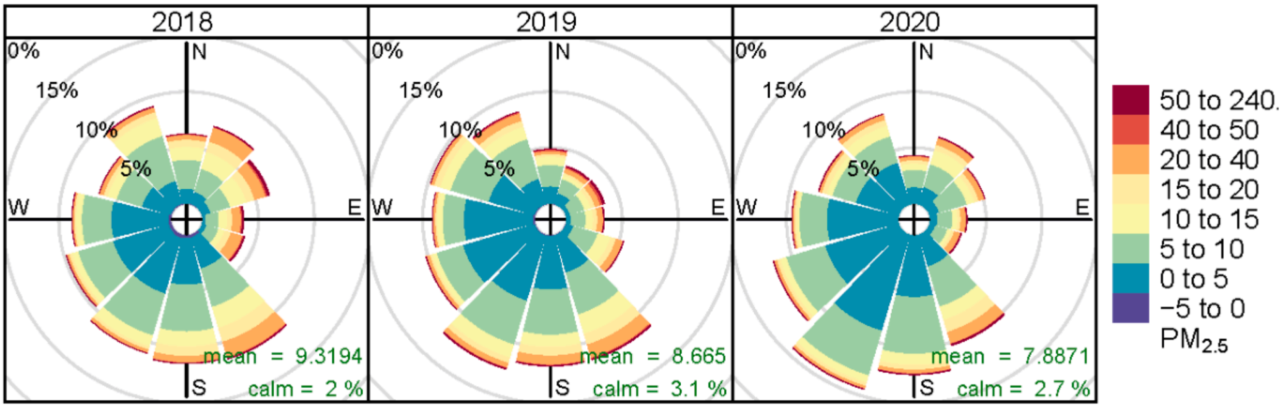

Fig. 4. Pollution rose showing wind direction and air quality, by class of $PM_{2.5}$ concentration (μgm^{-3}) for Ladywood Automatic Urban and Rural Monitoring Network (AURN) monitoring site, south-east of Birmingham, UK.

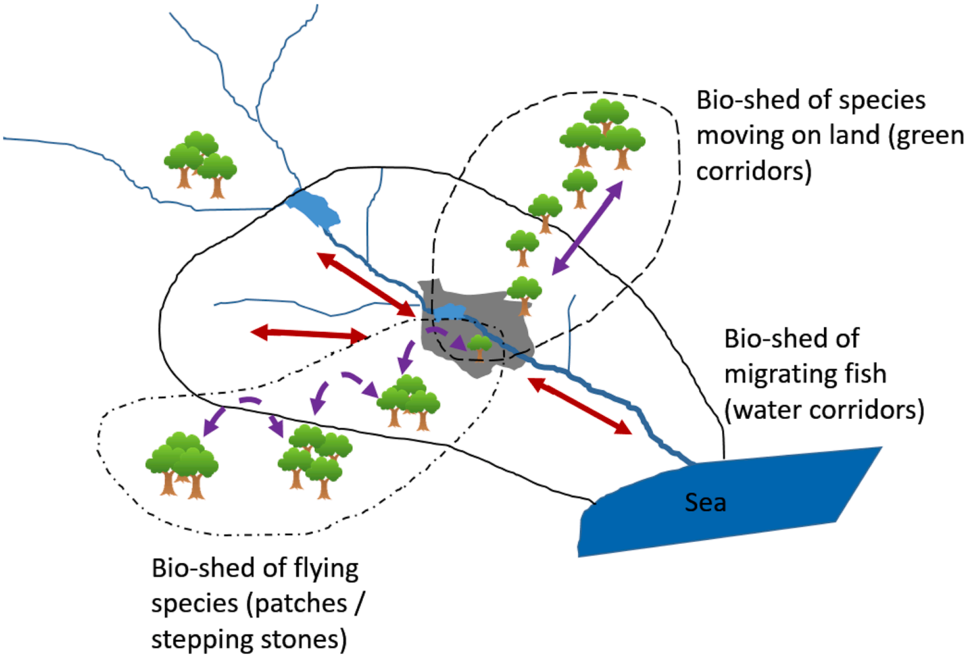

Fig. 5. Movement (and biosheds) of different organisms between urban and rural areas.

forage in rural areas. Other species spend most of their time in rural areas, but can move into urban areas to forage. Movement of black bears into urban areas is linked to food availability in rural areas [78]. Similar findings have been found in other species around the world, such as Langur monkeys in India during La Niña drought events [79]. Cities may also provide habitat or resources which are not available elsewhere or at certain times of the year. Some deer species in North America regularly move into or live in suburban areas to graze [80]. Birds can benefit from urban heat island effects through increased availability of food and warmer winter temperatures [81]. In high latitudes, the warmer urban temperatures often keep water bodies ice-free. Cities also provide open water and high vegetation cover in arid environments, and gardens and ornamental species provide nectar and other food sources for insects and birds. Longer-range interactions include migratory species which take advantage of the food and shelter that cities provide while on their migration routes.

2.3.2. Delineating biosheds

Following the principles of airsheds and watersheds, the term bio-shed is introduced to describe the area in which species move in relation to a city. The bioshed varies with the type of species, so there is no single shed, but each species has its own. Depending on how a species moves in the landscape (i.e. swimming, flying, crawling, walking), its size and requirement for shelter, rest or food, some species require densely connected green and blue-space corridors, while for other species, greenspace of a certain size, and within a certain distance is enough, forming stepping stones along which movement can occur.

2.3.3. Implications for location of NBS to benefit cities - Biodiversity

Optimising locations or management of NBS to benefit biodiversity needs to take account of multiple species needs. A meta-analysis across multiple taxonomic groups established that the main requirements are adequate patch size and connectivity [82]. Therefore, it is necessary to make sure that corridors and stepping stones of more natural habitats exist, both within the city to allow movement of species across an urban landscape where green and blue space are typically highly fragmented, but also between urban and rural areas. The structural and plant species diversity of these green and blue spaces is also important, as well as their connectedness. Design of such corridors can help connect and enhance high quality habitat within cities to that beyond the city boundaries. The needs of terrestrial species as well as birds and insects, and migratory water species like fish all need to be considered. The location and design of corridors and stepping stones should also balance potential negative consequences resulting from increased spread of invasive non-native species [83], but cannot always address the movement of problem species.

2.4. Resources

2.4.1. Spatial influences

The term resourceshed is used to describe the area within which resources are moved (Fig. 6). As resources we define food, biomass, minerals, energy and other materials, as well as waste. Almost all resources that cities consume come from elsewhere, to be transformed into buildings, infrastructure or living things including people, and ultimately become waste to be discarded and expelled to extra-urban areas [84,85]. The extra-urban areas which provide the resource requirement of cities have become increasingly global [86]. Therefore, the spatial interaction between cities and resources are complex and multiscale, from local to global.

Since the industrial revolution the area providing resource inputs has expanded dramatically. Before the industrial revolution, cities were mainly built using available materials from the surrounding areas and fed their inhabitants on local food production systems, particularly for perishable commodities like vegetables, meat and milk. Despite some high value commodities from long-distance trade networks, most resource flows were relatively local [87]. Cities in the XXI century now span their metabolic influxes across the globe in highly complex networks of supply chains, for resources such as fossil fuels, building materials and metal elements, as well as food [88]. The upstream resourceshed of cities is therefore the entire planet, with inputs controlled by market forces rather than ecological processes. Rates of resource turnover are also larger and faster than before. The material turnover of a modern citizen is one order of magnitude larger than in an ancient city of the same size [89].

Cities mainly play the role of resource consumer and waste producer, and resource cycling within cities is limited [90], although there is increasing focus on the circular economy via circular resource flows [91]. The output flows can be compartmented into goods, energy, and waste, and these have clearer spatial relationships. Goods are the manufactured products leaving cities and their sheds vary from local to global. Energy in the form of heat is emitted constantly from the city and exerts a very strong local effect within the city, augmenting urban heat island effects, but also has impacts outside the city, dissipated as a plume [92]. Waste is the more complex of the outflows and the sheds vary with the form of waste. Pollutant emissions to air and water can be considered as waste and exert local to longer distance effects, discussed under airsheds and watersheds in previous sections. Solid waste of low economic value, including organic wastes and consumer and construction waste, is mostly disposed of relatively close to cities, with a shed defined by the cost and method of disposal. However, higher value waste such as electronics or other products which can be reclaimed or recycled may be transported around the globe [93]. Some of these resource flows are mediated by natural biogeochemical cycles operating as a part of the ecosystem, for example, the water cycle, the carbon cycle, the nitrogen cycle, etc., and through biotic pathways [94], discussed in the previous sections.

2.4.2. Delineating resourcesheds

The resourceshed boundaries operate at multiple scales, which include both the immediate resourceshed of a city, and the remote sheds of the resources flowing in through multiple teleconnections [95]. As a result, the resourceshed is not easily delineated. The physical shed for resources obtained from within a country, such as food supplies, energy and construction materials is tangible, and both the location of resources as well as the transportation pathways can be quantified [96]. While considerably more complex, it is also possible to quantify the footprint of imported resources, and some of their secondary effects through techniques such as Life Cycle Analysis, natural capital assessment [97] and ecosystem services assessments, for example foot-printing of mining activity [98]. For the context of this paper, it is primarily the national and near-neighbour aspects of resourcesheds which are of relevance for siting and implementation of nature-based solutions. However, the remote aspects should not be forgotten, and are increasingly important for calculating the embedded or secondary impacts of the management of people, land and resources.

2.4.3. Implications for location of NBS to benefit cities - Resources

The NBS related to the production and transport of input resources are globally spread, transferring the effects of urban resource demand elsewhere, but NBS in those source locations can help to enhance or safeguard food, energy and materials provision and are extremely important in reducing the environmental footprint of cities and increasing their sustainability. The NBS which are most obvious in their

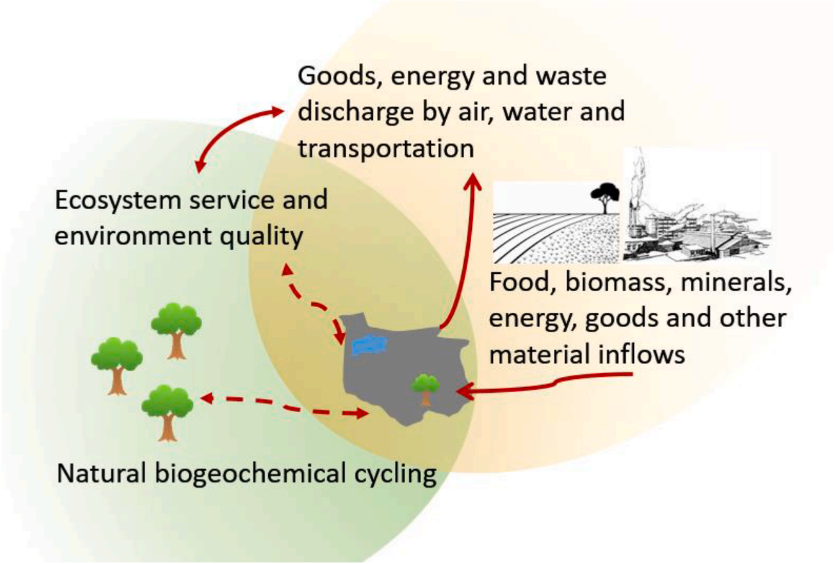

Fig. 6. Flows of resources between urban and extra-urban areas.

potential to mitigate locally directed waste streams, for example, heat, air and water, are discussed in the sections above. However, NBS are also relevant in the context of processing organic wastes, including food and human waste, linking in with natural biogeochemistry cycling and ecosystem service flows [99].

2.5. People

2.5.1. Spatial influences

Urban systems consist of people and their social and economic activities, including the infrastructure which supports those activities [100,101]. Green and blue space should be considered part of that urban infrastructure, and the urban system includes the functional linkages between locations which results in flows of goods, services and people (Fig. 7). The spatial distribution of people takes account of living, working, education, shopping and leisure activities. The locations for these activities may be centralised or decentralised, clustered or dispersed [102], but the locations, coupled with infrastructure such as transport and communication networks together define the types, distance, timing and direction of flows [103]. For example, commuting occurs primarily from residential areas within cities or commuter towns to locations for employment or education and has both a diurnal, and a weekly, pattern. Journeys for leisure will tend to peak in the evenings and at weekends and are defined by the type of leisure activity. Much longer-range flows include international tourism, flows for major national holidays such as around China's New Year, and flows of temporary workers, both of which may also have strong seasonal patterns. Flows follow from individual choices (and sometimes national policies) about which activities to undertake and when and where to do so. These decisions in turn are informed by the available options, and the limited (financial) means and time available [104,105]. Individuals balance the benefit of an activity with the associated cost and as a rule are willing to travel more for better experiences [106].

2.5.2. Delineating peoplesheds

The spatial scale of an urban peopleshed is not a fixed physical quantity, not does it follow an administrative boundary, but is defined by the opportunities it offers and the desire and ability of the population to engage with it. As a general principle more attractive places will be visited by more people and people are willing to travel greater distances to see them. Many people have a distinct set of green places that they interact with frequently, and others that are more attractive at a greater distance and which they visit less frequently [107]. The appreciation of green spaces by the population is also substantially coloured by their familiarity with and proximity to these spaces [108]. Thus, within the wider peopleshed of a city, individual green or blue space elements have their own peoplesheds.

People who live closer to a park tend to visit more often but visit for shorter periods, and they undertake different types of activities, such as daily exercise routines, dog-walking and spending time alone, which may only be partly related to park design; people who travel further to visit a park, especially larger regional and national parks, tend to stay longer and undertake activities based on active recreation or socialising [109].

Thus, for NBS offering recreational benefits, the associated peopleshed will depend on the quality and uniqueness of the opportunity that it offers, and to what extent it competes with other opportunities. This is recognised in typologies of green urban space that distinguish importance of greenspace at spatial scales ranging from 500 m (local) to 2000 m (neighbourhood) to functional urban area and regional / national levels [110].

2.5.3. Implications for location of NBS to benefit cities - People

Mechanisms of interaction of people with green and blue space include intentional, incidental and indirect interactions [111]. Understanding the variety of interactions can help design NBS for different sets of users, and address issues of equitability and environmental justice, particularly with respect to accessibility to greenspace [112,113]. Key to incorporating ideas around peoplesheds into NBS design is that people are mobile, and this brings additional flexibility into planning. It allows management of the infrastructure and other factors which encourage or facilitate movement of people, as well as the NBS themselves [114].

To maximise intentional engagement with greenspace, the best location is in the vicinity of the population that is underserviced and would have the most benefit from such development. NBS solutions that are further removed from the population, e.g. in peri-urban areas will need to be sufficiently attractive to draw visitors from longer distances and be well connected, especially by the public transport network. This is of relevance when considering equitable access as people deprived of access to greenspace may also not have access to a car. Green spaces are also enjoyed through incidental interactions in combination with other activities, for instance by tourists, shoppers and workers as they go about their other activities [115–117]. For maximising incidental engagement with greenspace, the logical place to locate NBS is along frequently travelled corridors or near places of outdoor activity. Indirect use of green spaces can positively affect the balance of outdoor and indoor living and the navigability of urban space by foot or bicycle [118,119].

Design of a park can take into account the surrounding demographics (the potential peopleshed), and build in features which cater for their needs, which may vary in accordance with factors such as socio-economic status and ethnicity. The optimal siting of an NBS will

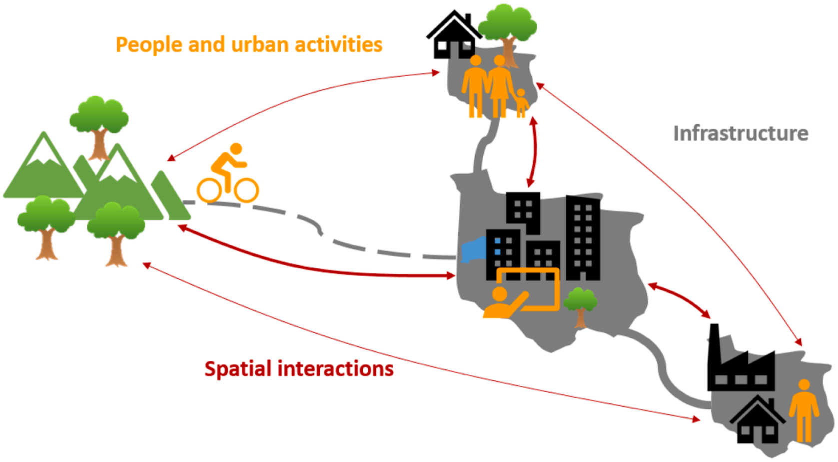

Fig. 7. Key components of the urban system which define flows of people and their social and economic activities.

depend on its intended purpose, such as to improve access to green space for casual day-to-day access, to facilitate more extensive leisure activities, to improve health and wellbeing, or to improve the existing flows and urban experience. In all cases the optimal location will depend on the existing population distribution, infrastructure, and flows of people. Ultimately however, the zone of interaction around an NBS will evolve, since every greenspace creates its own peopleshed which is fluid over time.

3. Interactions between domains

These domains do not exist in isolation, and there are numerous interactions among them, both in terms of the processes that operate, and the implications for how to manage NBS to mitigate wider adverse impacts. For example, air, water and biodiversity could interact via large scale tree planting to intercept air pollution. While the primary aim may be to improve air quality in urban areas, there may be additional benefits in terms of reduced flood risk from increased soil infiltration, and benefits for biodiversity, but there could also be adverse consequences for water availability through increased evapotranspiration and reduction of recharge into reservoirs or groundwater [120]. Management of green and blue space in urban areas has wide ranging impacts on biodiversity. Modifications to river or stream morphology (construction of culverts, local damming, etc.) have led to fragmentation of many urban streams, with consequences for natural fish migration. Trans-national issues of water governance historically focus on blue water, while the value of atmospheric water and green water and the potential for human intervention in their distribution has been largely neglected to date. However, it is an issue gaining increasing recognition [121,122] and illustrates the importance of interactions between airshed and watershed domains and the role of NBS.

4. Integrating the domains of environment and people

Effective planning of NBS interventions to improve the liveability and sustainability of cities is complex. It should take into account spatial and temporal variation in the pressure, the distances and directions over which services are provided, and the location and movement of the people who benefit. Thus, consideration of solutions also needs to understand the scales and spatial arrangements at which intra-extra-urban flows operate [28], noting that these may change over time. Combining an understanding of the various pressures affecting urban areas, the 'sheds' of the domains in which they operate and the scale and location of NBS, together with an understanding of peoplesheds, allows a wider conceptual paradigm – that we can manage both people and the environment to optimise the delivery of NBS. This leads to a more nuanced understanding of multiple interacting dimensions, which rarely overlap entirely but can be considered together to better plan and prioritise interventions to achieve multiple objectives for city dwellers (Fig. 8). In practical terms, by considering options and spatial relationships both within and outside cities, it gives opportunities to increase the benefit received by city dwellers from any particular NBS and reduce unintended trade-offs and negative interactions, resulting in more efficient and more sustainable cities.

For example, siting of woodland on the edge of a city rather than inside the city can achieve multiple objectives – woodland can be planted over a much larger area such that it clearly reduces air pollution concentrations, which would not be possible to the same extent with smaller planting schemes inside the city. At the same time it may also reduce agricultural runoff thereby improving water quality of rivers and potentially groundwater supplies, and can be designed with a variety of tree species combined with non-wooded habitats (open glades, heathland and water bodies) to maximise biodiversity. Since it is located near to the city, it also provides opportunities for recreation and

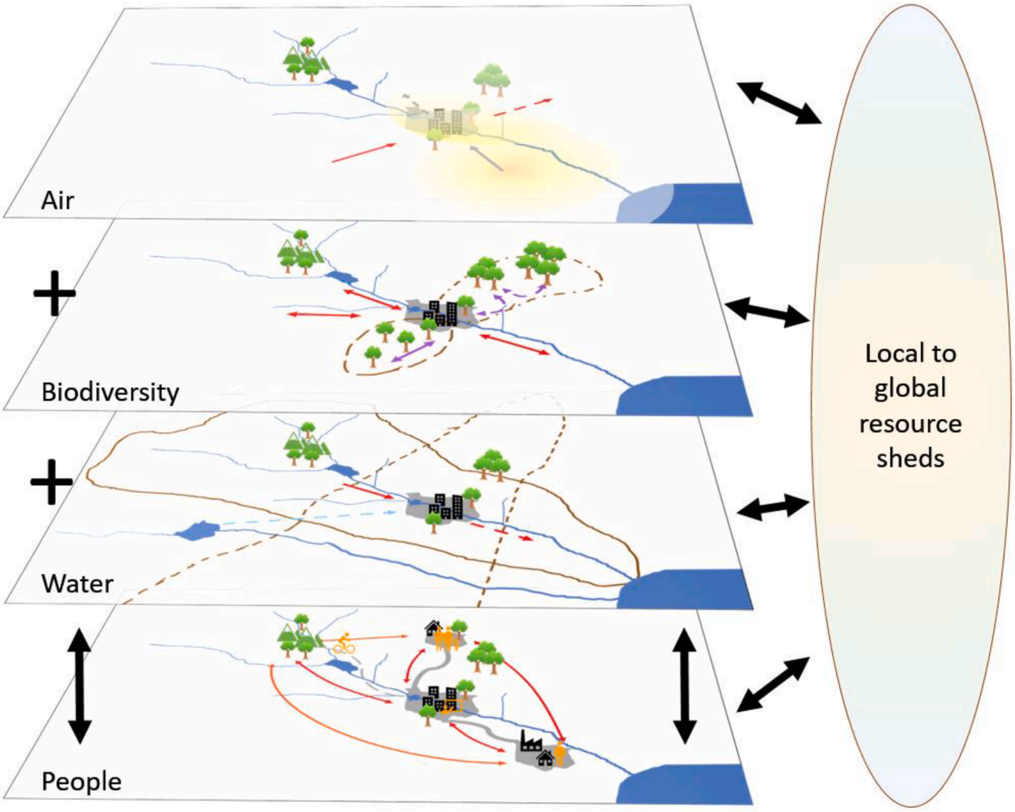

Fig. 8. Conceptual representation of NBS impacts in geographical space across domains, arrows are flows (e.g. of pollutants or people) to and from cities. Panels show the juxtaposition of complex natural sheds, peoplesheds and resource sheds to better plan NBS locations to benefit city dwellers.

improvement of physical and mental wellbeing. This additional wellbeing can be enhanced by designing aspects of built infrastructure within the woodland to make it more attractive and accessible to a wide range of users, (toilet facilities, food and drink, multi-access footpaths, play facilities for children), as well as the transport infrastructure to access the park (public transport, car parking, cycle paths). Lastly, the number of visitors can be managed by increasing the knowledge and perception of how attractive the location is to visit by advertising and encouraging use of the site through social networks (in other words, stimulating the elements of human, cultural and social capital which encourage people to interact with the site [123]. Accessibility for users is a key element supporting physical and mental well-being, which may have practical limitations for locations outside the city. Therefore, some trade-off analysis is always necessary, and particularly when considering actions in more distant locations, depending on the primary purpose for the intervention.

Integrating the domains of the environment and people in relation to urban and peri-urban also requires consideration of how we administrate NBS to reflect the interconnected nature of different natural ‘sheds’ that transcend administrative decision-making boundaries. Crucial here is the need to minimise the impacts of a decisions made in one jurisdiction on parts of the ‘shed’ administered by other authorities, and there can be substantial challenges when management decisions affect somebody’s local environment but the benefits are accrued mainly elsewhere. However, working together across jurisdictions also provides opportunities to use NBS to address certain large-scale pressures. Practice in this regard can vary depending on the political system in place (e.g. federal vs non-federal) and how varied powers are constitutionally allocated to different levels of decision making (e.g. national through to local). Some governance systems may be more geared up to this challenge than others - e.g. federal systems where greater coordination between decision making levels often occurs. Meanwhile, there are other decision-making systems in which integrated approaches can be followed to bridge across urban and cognate peri-urban administrations, such as integrated catchment management [124], and national policy integration [125]. Integrated decision making approaches for NBS in urban contexts are being implemented particularly in the area of water management [126]. For example, authorities in Genk, Belgium, have been working across administrative boundaries to develop a strategic green-blue link around the Stiemer river [127]. Approaches which consider adaptive governance are also being put into practice within planning and architecture, such as through the BREEAM Communities standard [128].

5. Conclusion

In this paper we show that the urban metabolism involves a wide range of material and non-material flows within ‘sheds’ which span urban, peri-urban, rural areas and beyond, which we collectively term the intra- and extra-urban. These flows can be categorised into different domains (encompassing air, water, biodiversity, resources, but also people) within which multiple interactions occur. These domains can operate at very different scales, and an understanding of how and where they operate can help to plan more sustainable cities for the benefit of urban residents. This wider perspective improves city design from a holistic perspective, to take account of the synergies and multifunctional benefits which can come about from carefully considering place and people, while avoiding potential disbenefits and trade-offs. It is worth recognising that there is no simple solution to some of the tradeoffs, but taking into account the spatial scales and interactions at which ecosystem service delivery occurs for different domains, as well as the implications for the many co-benefits that most interventions provide, can help to inform design of the most effective and holistic options.

Drawing on these findings, the design and planning of NBS to benefit cities can become more effective and thus generate more benefits by taking account of the following principles:

- Planning of interventions to benefit city residents should take into account the spatial reach and extent of the sheds for the key relevant domains.
- In the context of addressing a particular pressure, the domain can help decide on the best location for the type of NBS which mitigate its effects, but should include demand-mapping to achieve a balance across the pressure, the need to assess where the greatest benefit would occur, as well as the suitability of possible locations. Where multiple pressures co-occur, selecting and locating appropriate NBS across sheds is a more complex undertaking and requires tools which are capable of handling such levels of complexity.
- Decision-making should also take into account co-benefits, to help decide between locations where there are multiple options.
- All of this requires spatial and process-based models to assess the context-specific benefits, and co-benefits and trade-offs, of NBS in each location. Models should be appropriate for assessing the scale and reach of the NBS (i.e. take account the mechanisms by which the service operates, and any threshold-dependent effects).
- Implementation may require working across administrative boundaries, or with other relevant jurisdictions if necessary.
- The sheds approach can also be used as a communication tool to help achieved a shared understanding among stakeholders of the processes operating, and the likely optimum solutions and locations for NBS planning and management.

CRediT authorship contribution statement

Laurence Jones: Conceptualization, Funding acquisition, Writing – original draft, Writing – review & editing. **Stefan Reis:** Conceptualization, Writing – original draft, Writing – review & editing. **Mike Hutchins:** Conceptualization, Funding acquisition, Writing – original draft, Writing – review & editing. **James Miller:** Writing – original draft, Writing – review & editing. **Baihuiqian He:** Visualization. **Isabel Seifert-Dähnn:** Writing – original draft, Writing – review & editing. **Chong-Yu Xu:** Writing – review & editing. **Alex Hagen-Zanker:** Conceptualization, Writing – original draft, Writing – review & editing. **Jingyan Yu:** Writing – original draft, Writing – review & editing, Visualization. **Tao Lin:** Writing – original draft, Writing – review & editing. **Haifeng Jia:** Writing – review & editing. **Steven Loiselle:** Writing – review & editing. **Duncan Russel:** Writing – review & editing. **Clive E. Sabel:** Writing – review & editing. **David Fletcher:** Writing – review & editing. **Alice Fitch:** Visualization. **Luis Inostroza:** Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

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

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