STOTEN-152689; No of Pages 9

Science of the Total Environment 817 (2022) 152689

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

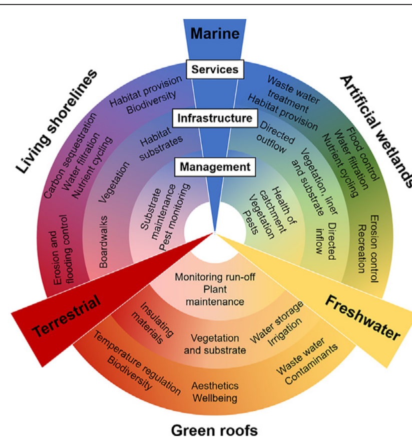
Discussion

Supporting urban ecosystem services across terrestrial, marine and freshwater realms

Elizabeth C. Lowe [a,*], Rochelle Steven [b,c], Rebecca L. Morris [d], Kirsten M. Parris [e], Axton C. Aguiar [f], Cameron E. Webb [g,h], Ana B. Bugnot [i,j], Katherine A. Dafforn [j,k], Rod M. Connolly [l], Mariana Mayer Pinto [j,m]

[a] Department of Biological Sciences, Macquarie University, NSW, Australia
[b] School of Biological Sciences, University of Queensland, Brisbane, QLD, Australia
[c] School of Biological Science, University of Western Australia, Perth, WA, Australia
[d] National Centre for Coasts and Climate, School of BioSciences, The University of Melbourne, VIC 3010, Australia
[e] School of Ecosystem and Forest Sciences, The University of Melbourne, VIC 3010, Australia
[f] School of Biological Sciences, University of Wollongong, NSW, Australia
[g] Medical Entomology, NSW Health Pathology, Westmead Hospital, NSW 2145, Australia
[h] Marie Bashir Institute of Infectious Diseases and Biosecurity, The University of Sydney, NSW 2006, Australia
[i] School of Life and Environmental Sciences, The University of Sydney, NSW 2006, Australia
[j] Sydney Institute of Marine Sciences, Mosman, NSW 2088, Australia
[k] Department of Earth and Environmental Sciences, Macquarie University, NSW 2109, Australia
[l] Australian Rivers Institute - Estuaries and Coasts, School of Environment and Science, Griffith University, Gold Coast, QLD, Australia
[m] Centre of Marine Science and Innovation, Evolution and Ecology Research Centre, School of Biological, Earth and Environmental Sciences, University of New South Wales, NSW, Australia

GRAPHICAL ABSTRACT



* Corresponding author.
E-mail address: lizzy.lowe@mq.edu.au (E.C. Lowe).

http://dx.doi.org/10.1016/j.scitotenv.2021.152689

ARTICLE INFO

Article history:
Received 14 December 2020
Received in revised form 20 December 2021
Accepted 22 December 2021
Available online 30 December 2021

Editor: Paulo Pereira

Keywords:
Aquatic ecology
Urbanization
Terrestrial ecology
Ecosystem function
Ecosystem processes

ABSTRACT

The terrestrial, freshwater and marine realms all provide essential ecosystem services in urban environments. However, the services provided by each realm are often considered independently, which ignores the synergies between them and risks underestimating the benefits derived collectively. Greater research collaboration across these realms, and an integrated approach to management decisions can help to support urban developments and restoration projects in maintaining or enhancing ecosystem services. The aim of this paper is to highlight the synergies and trade-offs among ecosystem services provided by each realm and to offer suggestions on how to improve current practice. We use case studies to illustrate the flow of services across realms. In our call to better integrate research and management across realms, we present a framework that provides a 6-step process for conducting collaborative research and management with an Australian perspective. Our framework considers unifying language, sharing, and understanding of desired outcomes, conducting cost-benefit analyses to minimise trade-offs, using multiple modes of communication for stakeholders, and applying research outcomes to inform regulation. It can be applied to improve collaboration among researchers, managers and planners from all realms, leading to strategic allocation of resources, increased protection of urban natural resources and improved environmental regulation with broad public support.

1. Introduction

The concept of ecosystem services was established to illustrate the benefits that functional environments provide to humans (Costanza et al., 1997; MA, 2003), and as a practical, albeit utilitarian, motivation to conserve ecosystems (Schröter et al., 2014). Wetlands in particular are highly valued for the many important global services they provide (Watson et al., 2018). While these ecosystems have traditionally received much attention, their contribution to wellbeing in urban areas and the services provided by urban-based ecosystems are often overlooked (Ziter, 2016; Locke and McPhearson, 2018). Yet, more people live in urban areas and interact with these ecosystems than outside them, with an estimated 54% of the world's population currently residing in urbanised regions and two out of three people expected to live in cities by 2050 (UN, 2015). Cities have been considered as 'both the problems and solutions to sustainability challenges of an increasingly urbanised world' (Grimm et al., 2008). For example, well designed high-density urban planning can limit destruction of natural landscapes, but the resulting intensified land-use can adversely impact the adjacent natural environment through other direct and indirect processes (e.g. noise, light, heat and physical pollution).

Nature based solutions are ecosystem modification, protection and management actions which support healthy societies and provide biodiversity benefits. In cities, 'nature-based solutions', such as planting trees and creating parks and green spaces, to restore ecological processes and enhance liveability are increasingly incorporated into urban planning (Roy et al., 2012; Keeler et al., 2019). However, ecosystem services are not limited to terrestrial systems and the provision of services often depends on the flow of biotic and abiotic elements between the terrestrial, freshwater and marine realms (Bishop et al., 2017). Understanding the connectivity between realms is fundamental to ensure the multiple beneficial services of urban ecosystems are effectively achieved. For example, increasing vegetation cover in urban areas is one of the key strategies to mitigate the adverse ecosystem and human-health impacts of urban heat-island effects (Tan et al., 2010) but the maintenance of urban vegetation requires irrigation, increasing water extraction from aquatic systems. To address these conflicts, management strategies aiming to maintain or restore ecosystems are more likely to be successful if we consider associations with other realms.

Incorporating the contributions of green and blue spaces to human health in cities is paramount to achieving sustainable urban planning goals but relies of appropriately designed research. There have been calls to review the ways researchers study the role of green space in human health (Labib et al., 2020) and, similarly, new perspectives are required to understand the importance of ecosystem services provided by realms in isolation as well as the linkages and potential impacts across realms (Bugnot et al., 2019). The majority of assessments of urban ecosystem services are primarily undertaken in a single realm (Hasse, 2015) with little acknowledgement of cross-linkages. For example, assessments are often limited to terrestrial realms in particular (Hasse, 2015) despite the extensive contribution that aquatic realms make to ecosystem services in cities (Dafforn et al., 2015), such as potable water, bioremediation, food, and cultural and recreational opportunities (Ziter, 2016). Focused research is required to improve sustainable planning by addressing knowledge gaps in the understandings of linkages between and across realms. In a recent review of urban ecosystem-service assessments by Ziter (2016), aquatic (marine and freshwater) realms were studied in fewer than 25% of papers, with only three of the 133 studies reviewed incorporating measures of a service in all three realms. Although the study of urban ecosystem services has advanced significantly, there are few studies that have looked at unintended consequences of management actions to enhance a desired service. This is an essential consideration because a management action may have a negative trade-offs both within and among realms (Keeler et al., 2019), especially in highly managed and complex urban ecosystems.

This study advances the review by Bugnot et al. (2019) that discusses how impacts originating from one realm can have large-scale effects, including causing impacts in other realms. Here, we go beyond impacts and explore how services provided by urban ecosystems, and their underlying functions, interact across realms. We advocate that the provision of many urban services is dependent on at least two realms and argue that sustainable cities will only be a reality with a holistic management approach that accounts for realm connectivity. We also discuss potential unintended negative consequences and trade-offs of interventions, emphasising the need for a holistic approach. We then provide three examples of integrated management projects designed to support urban services across realms as well as potential trade-offs and highlight new areas of research and collaboration for urban ecologists. Finally, we develop a framework targeted at both researchers and practitioners that bridges ecological concepts from all three realms with practice. This framework provides step-by-step practical, feasible recommendations to researchers, managers, and other relevant stakeholders on how to support the provision of services in urban areas by devising strategies that include all three realms.

2. Defining urban-ecosystem realms and the flow of ecosystem services

For the purpose of this article, 'realm' is defined, according to Bugnot et al. (2019), as a group of ecosystems that share common physical and ecological attributes and therefore tend to be studied or managed together. We recognise that this distinction is mostly conceptual, but it provides an intuitive framework on which to base the discussion presented here that considers the terrestrial, freshwater and marine realms.

An ecosystem service is broadly defined as a benefit that humans derive, directly or indirectly, from ecosystem functions (Costanza et al., 1997; MA, 2003) and conversely, an ecosystem disservice is a property of an ecosystem which has negative or unwanted effects. In an urban context, there is a need to consider not only the ecosystem services by the natural or semi-natural elements within an urban landscape but also the services provided by the cities themselves, such as green infrastructure (Tan et al., 2020). Urban ecosystem services can be described as regulating, provisioning, supporting and cultural (MA (2003) Table 1), which can be found in terrestrial, freshwater and marine realms, although the elements contributing to these services (i.e. different species, structures or abiotic elements) vary significantly between them (Table 1). We discuss the flows between realms in the context of these aggregations' hereafter.

The flow of services between realms is also important to cities. For instance, increasing urban terrestrial vegetation (by reduced clearing or active revegetation) can provide ecosystem services in terrestrial realms, as mentioned previously, but can also boost ecosystem services in other realms such as reduced storm water runoff (Jenerette et al., 2011), which in turn, can reduce the amount of pollutants entering adjacent freshwater and/or marine waterways (Davis and Birch, 2009). Excess nutrients that have entered freshwater ecosystems via runoff are a significant driver of declines in key aquatic species such as kelp (Gorman and Connell, 2009) and seagrass (Waycott et al., 2009), which provide functions including biodiversity conservation and nutrient cycling, and services such as carbon sequestration that underpin clean water and climate regulation. Thus, urban terrestrial vegetation as well as vegetation in transitioning areas to the marine realm, such as mangroves and saltmarshes, can support aquatic ecosystem services, but the benefits to systems are often overlooked due to management strategies that focus only on the terrestrial realm.

3. Trade-offs in ecosystem service management across realms

The multiple, complex and dynamic relationships among ecosystems services within and across realms means that management decisions designed to increase some services may lead to decreases in others or trade-offs. Strategies such as 'greening' urban infrastructure may enhance services between urban terrestrial and marine realms (see Bishop et al., 2017) and maximise the provision of a range of services from recreation and wellbeing to wastewater treatment and regulation of water flow between realms (Dafforn et al., 2015). However, where strategies such as these may facilitate the spread of invasive plants, there is a potential degradation of ecosystem services (Vallecillo et al., 2018). Although urban terrestrial vegetation provides multiple services to urban residents, park vegetation and street trees in drier climates often require supplemental

Table 1

A comparison of provisioning, regulating, supporting and cultural ecosystem services from urban terrestrial, freshwater and marine realms and examples of the elements providing each service (Derived from MA (2003) and FAO (2017)).

	Terrestrial	Freshwater	Marine
Provisioning			
Food	Plant, fungi, animals (urban agriculture, urban farms)	Fish, shellfish (fishery and aquaculture)	Fish, shellfish, algae (fishery and aquaculture)
Raw materials	Timber, minerals, hydrocarbons	Fresh water, sand/stones	Salt, minerals, sand, mangrove timber
Biochemical, medicinal, and pharmaceutical products	Plants, animals, fungi	Plants, animals, algae	Plants, animals, algae
Fresh water	Rainwater catchments, green roofs (storage of freshwater, water filtering)	Rivers, groundwater, wetlands, and dams (storage of fresh water), filter-feeders (water filtering), microbial communities (organic nutrient degradation)	Desalination plants (freshwater production)
Regulating			
Local climate air quality	Trees and vegetation (uptake of airborne pollutants, prevention of particle suspension)	Freshwater plants and algae (uptake of airborne pollutants)	Seaweed and phytoplankton (uptake of airborne pollutants)
Carbon sequestration and storage	Trees and other vegetation	Freshwater plants and algae, creek, and lake floors (storage of carbon)	Marine plants and algae, sedimentary habitats
Moderation of extreme weather events	Trees and permeable surfaces (regulating water flow and temperature)	Streams and freshwater wetlands (regulating water flow and temperature)	Seagrasses, mangroves, salt marsh, biogenic reefs (protection from storms and temperature regulation)
Erosion prevention and maintenance of soil fertility	Trees and other vegetation (prevents sediment erosion by water and wind and aids fertility through nutrient cycling)	Streams and wetlands (regulating water flow)	Seagrasses, mangroves, salt marsh, biogenic reefs (wave attenuation)
Pollination	Insect, bird, and mammal mediated pollination	Invertebrate mediated pollination of freshwater plants	Pollination of saltmarshes and mangroves
Waste-water treatment	Vegetation, green roofs, and walls (filtration and purification of grey water)	Wetlands (filtration and collection of wastewater)	Filter feeders, seagrasses, mangroves and saltmarshes (filtration and collection of wastewater)
Biological control	Invertebrate predators and parasites, birds, bats	Invertebrate predators and parasites, fish	Invertebrate predators and parasites, fish
Regulation of water flows	Vegetation, overland flow, green roofs	Riparian and wetland systems	Mangroves, seagrass, saltmarsh, biogenic reefs (wave attenuation and reduce flooding)
Supporting services			
Habitat for other species	Remnant vegetation, green space, built structures	Streams, canals, artificial wetlands	Built structures, remnant or restored coastal habitats
Maintenance of genetic diversity	All organisms present in the urban system	All organisms present in the urban system	All organisms present in the urban system
Cultural services			
Recreation, mental and physical health	Outdoor activities (hiking, camping, wildlife encounters)	Outdoor activities (fishing, boating, swimming, diving)	Outdoor activities (use of beaches, fishing, boating, swimming, diving)
Tourism	Wildlife tourism and farm tourism	Wildlife tourism, water sports, fishing, river cruises	Wildlife tourism, water sports, fishing, river cruises, diving, beaches
Spiritual experience and sense of place	Value for traditional peoples, connection with nature, meeting places	Value for traditional people, connection with nature, meeting places	Value for traditional people, connection with nature, meeting places
Aesthetic appreciation and inspiration for culture, art, and design	Green spaces, streetscapes	Water views, open space	Water views, beaches
Transport	Green spaces, streetscapes	Ferries and boats	Shipping and boat transport
Education	Citizen science, schoolyard science	Citizen science	Citizen science, educational foreshore trails

irrigation, and can consume more water than they infiltrate, thereby increasing the urban water-consumption footprint (Vico et al., 2014). Trees located near stormwater drains can also increase the nutrient loads of adjacent watersheds through leaf-litter deposition, contributing to the eutrophication of urban waterways (Janke et al. 2017). Trade-offs between multiple services such as those demonstrated above may arise in a range of urban systems and it is critical that relevant stakeholders make evidence-based decisions that balance these trade-offs, considering any potential unintended negative side-effects (Mayer-Pinto et al. 2019) and failing to integrate realms in decision-making may therefore create trade-offs in services provided by interacting realms (Bennett et al., 2009).

Management actions can have unintended consequences across realms via the creation of barriers to the movement of species or resources. The construction of artificial structures or diversion of waterways that may disrupt or degrade suitable habitat for some organisms. These actions modify ecological connectivity among realms, influencing important services. For example, the installation of culverts replaces natural stream vegetation with impervious surfaces, diminishing in-stream capacity to retain particles and adversely impacting water quality (Tippler et al., 2012). These particles remain in the water column and are transferred downstream to estuarine environments, affecting the conservation of biodiversity and productivity across realms (Sklar and Browder, 1998). Poor management of stormwater and freshwater runoff from terrestrial realms can also impact the flow of ecosystem services of downstream wetlands. This occurs through increased sedimentation and reduced salinity in critically important saltmarsh habitats, which can subsequently facilitate the encroachment of mangroves into other habitats bringing adverse impacts to local ecosystems (Kelleway et al., 2017; Geedicke et al., 2018). A common example of direct trade-offs between ecosystem services from different realms is the modification of natural coastal habitats (e.g. mangroves, corals and rocky shores) due to urban developments (Bulleri and Chapman, 2010). Loss of these key habitats has led to changes in the types of services supplied, such as decreased coastal protection in favour of human-centred needs such as the provision of real estate. Despite attempts to quantify and identify some of the synergies and trade-offs of ecosystem services across landscapes (Álvarez-Romero et al., 2011), we need a greater understanding of these interactions in urban areas, especially across realms in urban environments.

4. Multi-functional infrastructure to support services across realms

Increasingly, governments are investing in 'green' infrastructure within urban landscapes that can bring multiple benefits, with the ultimate goal of increasing human well-being and achieving sustainability in a highly urbanised world (Khoshnava et al., 2020; Airoldi et al., 2021). Space is a finite resource in urban areas and efforts to maximise benefits and minimise costs are driving increased innovation in the use of space for multiple purposes (Dafforn et al., 2015). In the case studies below, we discuss how technological advances and careful planning and design can create multi-functional urban infrastructure that incorporates connections across realms, maximising the provision of services.

a) **Living shorelines** provide stabilisation and protection for coastal cities, which are increasingly threatened by rising sea-levels and increases in storm surges (McInnes et al., 2003). The construction of hard structures such as seawalls, revetments and breakwaters have historically been the standard approach to coastal protection, but these can cause significant ecological damage and often disrupt important connections between the terrestrial and marine realms (Bishop et al., 2017). Living shorelines, are designed as a substitute or a complement to traditional artificial coastal defence structures using natural habitats, such as mangroves or dunes (Fig. 1a). For example, successes in restoring functioning mangrove ecosystems in the urban setting can be seen in Australia (e.g. Moreton Bay, Gold Coast (Lovelock et al., 2019)) and Fiji (e.g. Laucala Bay, Suva (Greenhalgh et al., 2018)). Managing such coastal and marine ecosystems can provide services including enhanced water quality (Needles et al., 2015), habitat provision, fishery enhancement, nutrient cycling and carbon sequestration. A key principle of living shorelines is that they maintain connectivity between aquatic and terrestrial systems, where food and nutrients are exchanged between realms, a process that is often obstructed by barriers created by traditional infrastructure (Bishop et al., 2017).

Fig. 1. Examples of multi-functional, multi-realm infrastructure initiatives: a) Living shorelines (Chesapeake Bay, Virginia, US), b) Green roofs (Paris, France) and c) Artificial wetlands (Sydney, Australia). Image credit: J. Hanford. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

b) **Green roofs** are designed to benefit terrestrial ecosystems by mitigating the urban heat-island effect, providing green space for cultural aesthetics (Fig. 1b), recreation and wellbeing, production of food, assistance in offsetting the greenhouse gasses, and habitat/biodiversity services (Vijayaraghavan, 2016). Well-designed green roofs, green walls and water-sensitive urban design have the potential to also benefit both freshwater and marine ecosystems. For example, plants with certain traits such as enhanced water storage and large root networks can be selected for their capacity to retain stormwater (Demuzere et al., 2014), thus reducing excessive runoff and contaminants entering water bodies (Pataki et al., 2011). The hydrological and heat moderation services of green roofs are primarily provided by the substrate, however careful choice of vegetation and planting medium can lead to the provision of additional ecosystem services leading to increased biodiversity and wellbeing (Hill et al., 2017). Examples of green roofs which have been designed to maximise provision of ecosystem services include: Chicago City Hall, United States (Dvorak and Carroll, 2008), the International Institute of Tropical Forestry in Río Piedras, Puerto Rico (Grullón-Penkova et al., 2020) and the proposed "Tengah, the Forest Town" in Singapore (Tan et al., 2021).
c) **Artificial wetlands** are commonly constructed in urban environments to intercept stormwater runoff from roads and streets to filter out harmful pollutants, thus maintaining water quality in the freshwater and marine realms (Fig. 1c). The services provided include: erosion control, water purification (through the action of filter feeders and microbial communities that go on to recruit in these wetlands(Lundholm, 2015)),recreation (e.g. used as urban parks), and treatment of wastewater (filtration via plants, recycling nutrients, sedimentation of heavy metals, filter feeding animals, microbial communities(Leigh et al., 2013)). Artificial wetlands also provide aesthetic value for wildlife tourism and recreational activities, including birdwatching (Levy, 2015). However, care must be taken in the design and maintenance of these habitats to ensure that while the objectives of improved water quality and increased biodiversity are met, unintended adverse consequences are avoided. For example, stormwater wetlands can act as ecological traps for frogs (Sievers et al., 2018), while stagnant water can support increased mosquito populations in urban areas (Hanford et al., 2019). The response to pest and public health concerns may, in turn, result in application of insecticides or habitat modification that results in long term ecological damage and may diminish ecosystem services. These unintended consequences can, alternatively, be managed through provisioning habitat features that create less suitable conditions for mosquitoes (Russell, 1999) or that attract the natural biological controls for mosquitoes (i.e. frogs, dragonflies and other aquatic fauna).

5. A framework for integrating cross-realm research and management

There are a number of challenges that need to be overcome to maximise the support of ecosystem services across all urban realms. Multidisciplinary, multi-realm research can determine which strategies can be applied in different urban ecosystems, but clear processes are needed to improve the current lack of integration across realms in urban-development practices. For instance, a report summarising the main challenges regarding water environmental management in 13 Asian countries, including Japan, China and Indonesia (WEPA, 2012), identified challenges to improve water quality in these areas but largely ignored linkages across realms, with the exception of residential and industrial discharges.

Frameworks that outline a procedure for cooperative management can significantly improve management outcomes in urban areas, especially when multiple interest groups are involved (Bastian et al., 2012). For example, the draft Yarra Strategic Plan sets out a 10-year plan for the corridor of the Yarra River (Birrarung) in Melbourne, the second biggest city in Australia, home to >5 million people (VictorianGovernment, 2020). The plan explicitly considers the terrestrial realm along the entire length of the river from its headwaters to Port Phillip Bay, including planning controls, management of parklands for recreation and other ecosystem services, and how activities on land influence the services provided by the freshwater realm. The draft strategic plan has been developed collaboratively by representatives of the Traditional Owners, the Wurundjeri Woi wurrung Cultural Heritage Aboriginal Corporation, and the 15 government agencies involved in managing the river. However, this type of collaborative, cross-realm approach remains rare. From the available plan it is not evident whether the government has done a cost-benefit analyses (as outlined in our proposed framework) to determine the priority actions of the plan and, importantly, inform future projects.

In an international context, the European 'Green Surge' project, which aims to advance the development of urban green infrastructure in European cities, provides a good example of a multi-realm framework. The project adopts an inter- and transdisciplinary approach and considers the linkages between urban green and blue spaces in terrestrial and aquatic realms, respectively, as well as their biodiversity and ecosystem services. Importantly, the project provided evidence on the ecosystem services and benefits generated by urban green spaces, when adopting a holistic approach (Pauleit et al., 2019). Based on successful programs including the European Water Framework Directive (2000/60/EC), we developed a six-step framework to integrate management of ecosystem services across realms in an Australian context. This framework can be used to ensure that the goals and desired outcomes of all collaborators are understood and that the processes underlying the provision of ecosystem services are supported through all research and management decisions (Fig. 2). Importantly, this framework can also be applied to address local problems across different countries (see example below).

1) **Create multi-disciplinary and multi-realm teams:** To maximise the support and provision of urban ecosystem services across realms, a team needs to be assembled from researchers and practitioners from different fields/management areas. These teams should consist of engineers, land managers, economists, architects, financiers, ecologists, builders and developers. Additionally, regulators should also be included so that positive outcomes of proposed works can be quickly and directly translated into policy (see last step of the framework).
When and by whom such teams should be formed/convened will depend on the specific issue to be solved/discussed and the desired outcome. For example, if the desired outcome is to minimise impacts from coastal industry/developments to improve fisheries and coastal community livelihoods, then local and state government should coordinate efforts to form a team that includes fisheries researchers, economists, ecologists, social workers, relevant industry stakeholders (from the terrestrial and marine realms) and the public living in those communities.
2) **Unify language for communication across realms and stakeholders:** A vital component of cooperation across disciplines is unifying the terminology used by researchers and practitioners in all three realms (see further discussion e.g. in Cole, 2005; Bugnot 2019). We suggest that any collaborative, cross-realm project should create a glossary of technical terms and their definitions for key stakeholders. We also recommend eliminating the use of acronyms that are specific to individual realms and/or area of expertise or stakeholder group. For example, local managers that are responsible for aquatic habitats are likely to have a completely different set of acronyms to industry stakeholders that deal mostly in terrestrial systems, and community members may not be familiar with any of the acronyms used.
3) **Focus on outcomes:** This stage needs to clearly identify the key goal/target that needs to be achieved. This will determine which variables should be measured/considered and why, focusing on interconnected outcomes. In the context of urban ecosystem services, focusing on outcomes means measuring the processes themselves and the services they underpin, which are quite general across realms (Webb 2012; Table 1), rather than focusing on the underlying mechanisms that are specific to each realm (see Table 1). For instance, when planning to plant street trees in coastal cities or designing 'green roofs' for buildings,

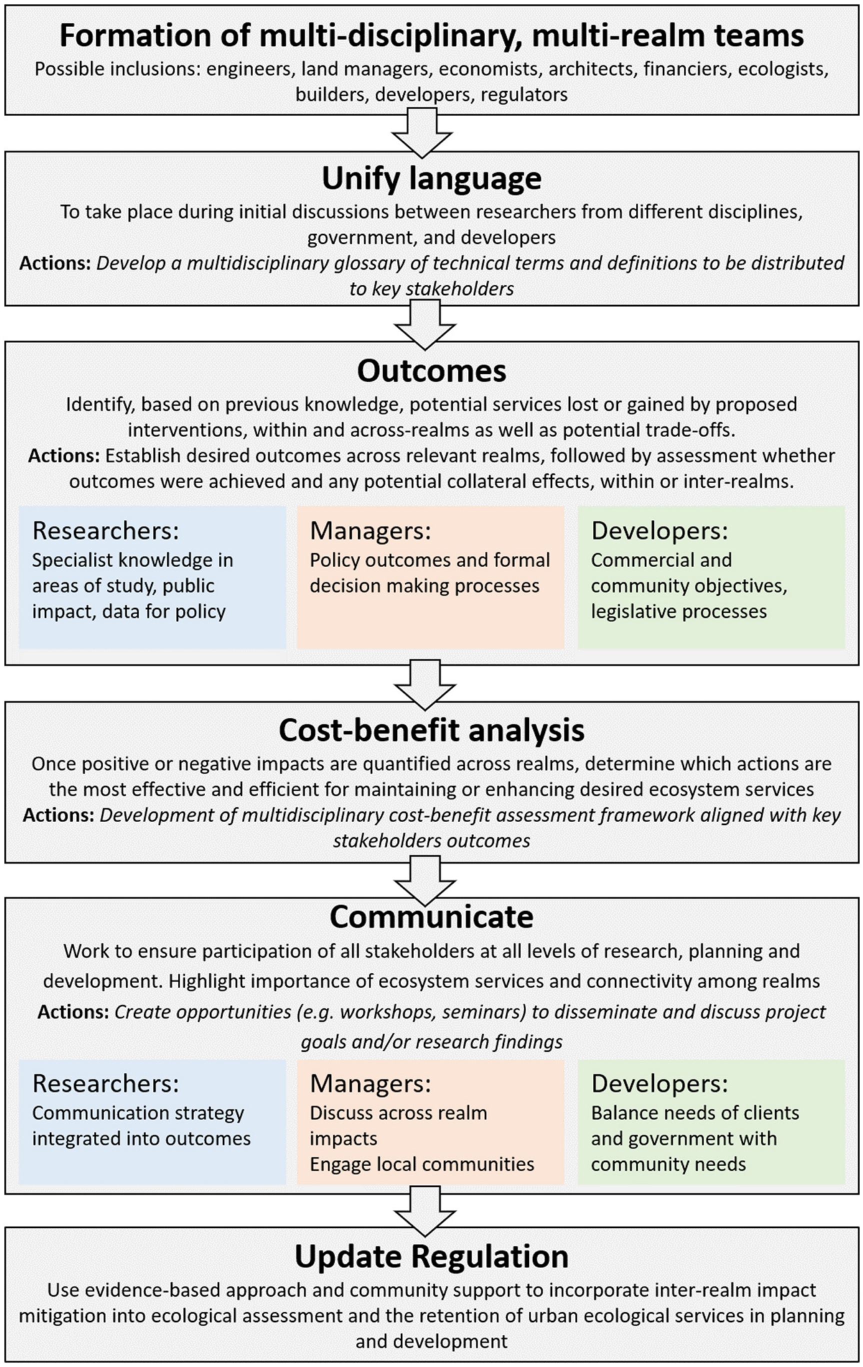


Fig. 2. Flow chart for recommendations to improve the research, planning and management of ecosystem services across realms.

ecological researchers need to work with practitioners to measure key variables on land such as habitat provision, urban-heat mitigation and mitigation of air pollution, while also planning for how much water is needed to maintain these green spaces. Similarly, when designing a living shoreline, measurements should include habitat provision per unit area (on land and in the sea), rates of coastal erosion, pollution mitigation (on land and in the sea) and food production (e.g. fisheries). See extensive discussion on management of urban areas in Threlfall et al. (2021).

4) **Cost-benefit analysis.** The measurement of variables as outlined above is essential for managers and other stakeholders to make a full cost-benefit analysis, weighing the pros and cons of such interventions (Fig. 2). For example, services provide by the interventions above need to be compared to those in areas without street trees, green roofs or living shorelines, to gain understanding of the full suite of impacts. A global collaborative approach is also beneficial here, as the results of interventions in one city may be used to inform new planning developments in other cities with similar impacts. This analysis should be based on the needs of all relevant stakeholders and decision-makers, from each realm, taking into consideration economic, ecological and social costs and benefits.

5) **Communication with other stakeholders:** The next step is to ensure that planning strategies and outputs are clearly communicated to stakeholders that might not have been present at the initial steps (Fig. 2). In practice, this could be done through direct engagement at either face-to-face workshops or seminars that communicate the key elements needed in planning and development. For example, researchers need to clearly communicate the importance of evidence-based management

approaches and how science can inform decisions. This can be done through community talks to inform the general public or through other platforms, such as presentations in conferences or symposiums that are well attended by policy-makers, managers and scientists as well as webinars targeted to specific stakeholders such as developers that might not have been involved in the initial stages for a variety of reasons. Support from the community is essential to achieve desired outcomes in urban spaces (Abelson et al., 2016). Management and strategies to support urban ecosystem services across realms will rarely achieve their targets/goals if the needs and worries of the general public and other relevant stakeholders, who are often the most direct recipients of such services, are disregarded. Initiatives such as the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) are a good example of how multiple stakeholders can be brought together with the aim of enhancing communication and ensuring sustainable practice across research and government. There is also enormous potential to get the public involved by using citizen science which, when limitations such as data quality are well managed, can be used to both obtain ecological data about how and where biodiversity persists on private land (Van Helden et al., 2020) and to promote public engagement regarding issues of ecosystem services in all realms (Buytaert et al., 2014).

6) **Update regulation:** The final stage of a cross-realm research/management framework relates to working collaboratively to inform and improve regulation. While there is legislation and other planning policies in place that regulate urban planning and environmental protection, there are often strict jurisdiction or geographic boundaries, which ignore the risk of cross realm impacts. This is highlighted in the complexity of static planning decisions applied under different levels of government to dynamic ecosystems at high risk of adverse impacts from surrounding realms (Rogers et al., 2016).
Planning regulations and guidelines tend to lead to the loss of ecosystem services in cities rather than their retention due to the priorities given to urban growth. For example, some biodiversity offsets in planning approvals do not achieve their biodiversity targets and yet developments are still allowed to proceed (Maron et al., 2016; Sonter et al., 2017). The ecological assessments of new developments are also moderated by the developer, which is a significant conflict of interest (Wotherspoon and Burgin, 2009) and can lead to uncertainty where there is overlap in environmental protection legislation or the realms in which they apply. In some instances, there may not necessarily be mechanisms in place to address potential cross-realm adverse impacts associated with specific planning decisions. This issue may need to be addressed by establishing opportunities to collaborate with authorities responsible for planning decisions (e.g. local government). This will require assurances that overlapping legislation or planning policies are crossed checked by relevant departments.
Despite the efforts of compliance officers employed by governments to counter these challenges and sources of conflict, inappropriate development approvals and conditions on approval continue to plague cities under rapid development pressure (Moore et al., 2017). So long as the regulatory system fails to demand inclusion of inter-realm impact mitigation, the aforementioned research will go unacknowledged in the development process. A potentially effective initiative to address these problems is the development of interaction pathways between planning instruments with cross realm implications (e.g. asset protection zones in terrestrial areas that may impact adjacent aquatic ecosystems). These pathways may provide a workflow for compliance officers to identify and/or mitigate site-specific cross realm impacts. Importantly, the inclusion of regulators from all three realms in the initial team (as outlined in step 1) is one of the ways in which such challenges can be quickly identified and subsequently overcome.

One of the most important situations in which to implement this framework are in 'transition zones' such as estuaries, mangroves and wetlands undergoing high levels of development. To demonstrate the utility of the proposed framework, we outline a theoretical scenario in which the framework is applied to a constructed wetlands within an urban setting (Table 2). Constructed wetlands are an increasingly common feature of urban areas around the world to assist management stormwater pollution (Malaviya and Singh, 2012). They also have the potential to be used to enhance terrestrial, freshwater, and marine biodiversity, assist mitigation of climate change impacts, and improve the health and wellbeing of the community but they may also provide disservices such as methane production

Table 2
Key advantages associated with each of the steps within the proposed framework when applied to constructed wetlands for the management of urban stormwater, ecosystem conservation, and mosquito management.

Framework step	Advantages
Create multi-disciplinary and multi-realm teams	■ Maximise co-benefits of land use (e.g. design of adjacent parklands for recreation and/or additional wildlife habitats; provide foreshore habitat enhancement in conjunction with wetland discharge infrastructure) ■ Integrate site-specific cross realm biodiversity objectives (e.g. wetlands designed to provide foraging habitat for fishing bats; roost sites in adjacent terrestrial vegetation for local bird species). ■ Minimise risk of adverse impacts to adjacent marine ecosystem (e.g. foreshore erosion, adverse impact on seagrass) ■ Mitigate ecosystem disservices associated with mosquitoes where conflicts existing between engineering of water bodies and enhanced conditions for mosquitoes (e.g. water depth, aquatic vegetation planting densities).
Unify language for communication across realms and stakeholders	■ Shared glossary (i.e. wetland design, function, and biological attributes) used by realm specific ecologists, engineers, landscape designers and other stakeholders to minimise confusion may arise resulting in actual and potential outcomes (e.g. a recommendation of "rock lined" bioretention basin may be constructed with rocks lining the bottom, as opposed to only the margins, of the waterbody, making maintenance operationally difficult, reduce ecological health, and subsequently predispose the wetland to mosquito production).
Focus on outcomes	■ Prioritise multi realm benefits over single realm benefits where possible (e.g. water quality objectives that are independent of ecological habitat provisions for key local species) ■ A disproportionate focus on minimising ecosystem disservices (e.g. mosquito impacts) may limit ecosystem services otherwise provided for terrestrial and/or aquatic wildlife (e.g. frog habitat)
Cost-benefit analysis	■ Extend economic assessment beyond construction phase of wetlands ■ Consider cross realm co-benefits (e.g. loss of recreational utility; financial costs to authorities or residents to undertake mosquito control).
Communication with other stakeholders	■ Communication within local authorities (e.g. stormwater, natural resources, environmental health, planning) and outside stakeholders is critical to capture cross realm benefits
Update regulation	■ Address conflicts between legislation that specifically apply to individual realms (e.g. water quality and discharge to downstream waterways may be in conflict with legislation regulating conservation of aquatic habitats; strategies to enhance terrestrial realm ecosystems may need to be traded off against asset protection legislation associated with bushfire or flood protection).

(Whiting and Chanton, 2001) and increased mosquito populations (Hanford et al., 2019). There can be conflicts in obtaining these objectives and trade-offs are required. In applying the proposed six-step framework to integrate management of ecosystem services across realms, we provide examples of the advantages as they apply to constructed wetlands and surrounding environments within an urban land use context in Australia (Table 2).

In addition to the scenario outlined above, a real world example of where our framework could be applied is Guanabara Bay in Rio de Janeiro (Fries et al., 2019) which is of high importance for industry, recreation, and tourism, but also has significant ecological value. Guanabara Bay is a natural tropical embayment in Brazil and its watershed supports 8.6 million people, with urbanization trends showing that growth is rapidly expanding to peripheral areas of the Bay as well as the seafront (Fries et al., 2019). Management plans to improve the water quality of the bay which is increasingly threatened by discharges of untreated sewage and industrial run-offs have recently been developed (PFGGBG, 2016). In this case, the current management plan does explicitly consider linkages between the marine habitats within the bay with terrestrial and freshwater ecosystems. For example, recognising the impact of the discharge of trash and untreated sewage into the bay due to the uncontrolled population growth and lack of sanitation services on the water quality as well as the importance of the native vegetation in the surrounded, urbanised areas.

Encouragingly, the management plan seems to have been developed with the input of a wide range of stakeholders (step 1 of our proposed framework). However, the goals outlined in the Guanabara Bay management seem to be focused on actions rather than on outcomes as proposed here. For example, stated goals include: 'increasing human and industrial wastewater treatment and collection' (see e.g. Fries et al., 2019). Arguably, a more appropriate goal would be focused on services – such as improved water quality to allow/increase recreational and tourist activities. This is because, increases in sewage treatment might not always translate into tangible improvements of the water quality and/or services derived from it.

Even goals that are more focused on outcomes themselves - such as the goal 'to promote sustainable fisheries' - lack further details and/or specific measures attached to it. For example information on how 'sustainable fisheries' translates into catch per unit or which species will be targeted. Following the proposed framework here would allow the development of clear objectives for the Bay and consequently, a rapid and relatively easy evaluation of whether management actions have been successful or not. This would likely lead to the implementation and/or update of relevant regulation as outlined in the last step of our framework.

As interest in urban sustainability initiatives increase, there is a growing trend in researching the ecological and financial costs and benefits. One recent example is the comprehensive assessment of stormwater management through green infrastructure in Villanova, Pennsylvania, USA, within a 'Life Cycle Assessment' framework. This framework considers the identification and quantification of all relative inputs and outputs throughout the life cycle of the infrastructure, as well as across realm factors, such as wildlife habitat in terrestrial zones or downstream wetland impacts (Flynn and Traver, 2013). With an ongoing focus on providing economic assessments of urban ecosystem services, it is critical that interactions between realms are considered as opposed to a focus on individual habitats or realms in isolation (Capriolo et al., 2020).

6. Conclusions

Researchers have the important role of providing the evidence required for better integration of multiple realms into planning decisions and the development of multi-functional infrastructure. Ensuring all ecological realms affected by urban development actions are given consideration, and that all human communities are included as key stakeholders will improve development outcomes and, ultimately, urban liveability in our major cities. We hope that our synopsis of well-integrated projects and suggestions for a collaborative research framework will help to improve engagement between researchers working in different realms; encourage clear communication of the benefits and complexity of healthy urban ecosystems to the wider community; and in particular, highlight the importance of maintaining ecosystem services across all three realms.

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.

Acknowledgements

This manuscript arose from a workshop funded by the Sydney Institute of Marine Science Foundation (NSW, Australia) and Mosman Council (NSW, Australia). We thank Amy Hahs for help coordinating the workshop and establishing the themes of the papers, and Jayne Hanford for providing the photo of an artificial wetland. AB and KAD were supported by the Australian Research Council through a Linkage Grant (LP140100753) awarded to KAD. KMP and RS were supported by the Australian Government's National Environmental Science Program through the Clean Air and Urban Landscapes Hub and the Threatened Species Recovery Hub. RLM was supported by the National Centre for Coasts and Climate, funded through the Earth Systems and Climate Change Hub by the Australian Government's National Environmental Science Program. RMC was supported by an Australian Research Council Discovery Project (DP150102271) and The Global Wetlands Project. This is SIMS manuscript #282.

CRediT authorship contribution statement

Author	Conception and design of manuscript	Drafting outline	Drafting article	Drafting figures and/or tables	Editing manuscript	Approved final version
E. C. Lowe	x	x	x	x	x	x
M. Mayer Pinto	x	x	x	x	x	x
A. C. Aguiar	x	x		x		x
R. L. Morris	x	x	x	x	x	x
K. M. Parris	x	x	x		x	x
R. Steven	x	x	x	x	x	x
C. E. Webb	x	x	x	x	x	x
A. B. Bugnot	x	x	x		x	x
K. A. Dafforn	x	x	x		x	x
R. M. Connolly	x	x	x		x	x

References

Abelson, A., Halpern, B.S., Reed, D.C., Orth, R.J., Kendrick, G.A., Beck, M.W., Belmaker, J., Krause, G., Edgar, G.J., Airoldi, L., 2016. Upgrading marine ecosystem restoration using ecological-social concepts. Bioscience 66, 156–163.

Airoldi, L., Beck, M.W., Firth, L.B., Bugnot, A.B., Steinberg, P.D., Dafforn, K.A., 2021. Emerging solutions to return nature to the Urban Ocean. Annu. Rev. Mar. Sci. 13 null.

Álvarez-Romero, J.G., Pressey, R.L., Ban, N.C., Vance-Borland, K., Willer, C., Klein, C.J., Gaines, S.D., 2011. Integrated Land-Sea conservation planning: the missing links. Annu. Rev. Ecol. Evol. Syst. 42, 381–409.

Bastian, O., Haase, D., Grunewald, K., 2012. Ecosystem properties, potentials and services – the EPPS conceptual framework and an urban application example. Ecol. Indic. 21, 7–16.

Bennett, E.M., Peterson, G.D., Gordon, L.J., 2009. Understanding relationships among multiple ecosystem services. Ecol. Lett. 12, 1394–1404.

Bishop, M.J., Mayer-Pinto, M., Airoldi, L., Firth, L.B., Morris, R.L., Loke, L.H.L., Hawkins, S.J., Naylor, L.A., Coleman, R.A., Chee, S.Y., Dafforn, K.A., 2017. Effects of ocean sprawl on ecological connectivity: impacts and solutions. J. Exp. Mar. Biol. Ecol. 492, 7–30.

Bugnot, A.B., Hose, G.C., Walsh, C.J., Floerl, O., French, K., Dafforn, K.A., Hanford, J., Lowe, E.C., Hahs, A.K., 2019. Urban impacts across realms: making the case for inter-realm monitoring and management. Sci. Total Environ. 648, 711–719.

Bulleri, F., Chapman, M.G., 2010. The introduction of coastal infrastructure as a driver of change in marine environments. J. Appl. Ecol. 47, 26–35.

Buytaert, W., Zulkafli, Z., Grainger, S., Acosta, L., Alemie, T.C., Bastiaensen, J., Bièvre, B.De, Bhusal, J., Clark, J., Dewulf, A., Foggin, M., Hannah, D.M., Hergarten, C., Isaeva, A., Karpouzoglou, T., Pandeya, B., Paudel, D., Sharma, K., Steenhuis, T., Tilahun, S., Hecken, G.Van, Zhumanova, M., 2014. Citizen science in hydrology and water resources: opportunities for knowledge generation, ecosystem service management, and sustainable development. 2.

Capriolo, A., Boschetto, R.G., Mascolo, R.A., Balbi, S., Villa, F., 2020. Biophysical and economic assessment of four ecosystem services for natural capital accounting in Italy. Ecosyst. Serv. 46, 101207.

Costanza, R., d'Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neill, R.V., Paruelo, J., Raskin, R.G., Sutton, P., van den Belt, M., 1997. The value of the world's ecosystem services and natural capital. Nature 387, 253.

Dafforn, K.A., Glasby, T.M., Airoldi, L., Rivero, N.K., Mayer-Pinto, M., Johnston, E.L., 2015. Marine urbanization: an ecological framework for designing multifunctional artificial structures. Front. Ecol. Environ. 13 (2), 82–90.

Davis, B.S., Birch, G.F., 2009. Catchment-wide assessment of the cost-effectiveness of stormwater remediation measures in urban areas. Environ. Sci. Pol. 12, 84–91.

Demuzere, M., Orru, K., Heidrich, O., Olazabal, E., Geneletti, D., Orru, H., Bhave, A.G., Mittal, N., Feliu, E., Faehnle, M., 2014. Mitigating and adapting to climate change: multi-functional and multi-scale assessment of green urban infrastructure. J. Environ. Manag. 146, 107–115.

Dvorak, B., Carroll, K., 2008. Chicago City Hall green roof: its evolving form and care. The Sixth Annual International Rooftops for Sustainable Communities Conference. Cardinal Group, Toronto, Baltimore, MD.

FAO, 2017. Food and Agriculture Organization of the United Nations. Ecosystem Services & Biodiversity (ESB).

Flynn, K.M., Traver, R.G., 2013. Green infrastructure life cycle assessment: a bio-infiltration case study. Ecol. Eng. 55, 9–22.

Fries, A.S., Coimbra, J.P., Nemazie, D.A., Summers, R.M., Azevedo, J.P.S., Filoso, S., Newton, M., Gelli, G., de Oliveira, R.C.N., Pessoa, M.A.R., Dennison, W.C., 2019. Guanabara Bay ecosystem health report card: science, management, and governance implications. Reg. Stud. Mar. Sci. 25, 100474.

Geedicke, I., Oldeland, J., Leishman, M.R., 2018. Urban stormwater run-off promotes compression of saltmarshes by freshwater plants and mangrove forests. Sci. Total Environ. 637–638, 137–144.

Gorman, D., Connell, S.D., 2009. Recovering subtidal forests in human-dominated landscapes. 46, pp. 1258–1265.

Greenhalgh, S., Booth, P., Walsh, P., Korovulavula, I., Copeland, L., Tikoibua, T., 2018. Mangrove restoration: An overview of the benefits and costs of restoration. Prepared as part of the RESCCUE-SPC Fiji project. University of South Pacific, Institute of Applied Sciences, Suva, Fiji.

Grimm, N.B., Faeth, S.H., Golubiewski, N.E., Redman, C.L., Wu, J., Bai, X., Briggs, J.M., 2008. Global change and the ecology of cities. Science 319, 756–760.

Grullón-Penkova, I.F., Zimmerman, J.K., González, G., 2020. Green roofs in the tropics: design considerations and vegetation dynamics. Heliyon 6.

Hanford, J.K., Webb, C.E., Hochuli, D.F., 2019. Habitat traits associated with mosquito risk and aquatic diversity in urban wetlands. Wetlands 39, 743–758.

Hasse, D., 2015. Reflections about blue ecosystem services in cities. Sustain. Water Qual. Ecol. 5, 77–83.

Hill, J., Drake, J., Sleep, B., Margolis, L., 2017. Influences of four extensive green roof design variables on stormwater hydrology. J. Hydrol. Eng. 22, 04017019.

Jenerette, G.D., Harlan, S.L., Stefanov, W.L., Martin, C.A., 2011. Ecosystem services and urban heat riskscape moderation: water, green spaces, and social inequality in Phoenix, USA. Ecol. Appl. 21, 2637–2651.

Keeler, B.L., Hamel, P., McPhearson, T., Hamann, M.H., Donahue, M.L., Meza Prado, K.A., Arkema, K.K., Bratman, G.N., Brauman, K.A., Finlay, J.C., Guerry, A.D., Hobbie, S.E., Johnson, J.A., MacDonald, G.K., McDonald, R.I., Neverisky, N., Wood, S.A., 2019. Social-ecological and technological factors moderate the value of urban nature. Nat. Sustain. 2, 29–38.

Kelleway, J.J., Cavanaugh, K., Rogers, K., Feller, I.C., Ens, E., Doughty, C., Saintilan, N., 2017. Review of the ecosystem service implications of mangrove encroachment into salt marshes. Glob. Chang. Biol. 23, 3967–3983.

Khoshnava, S.M., Rostami, R., Zin, R.M., Kamyab, H., Abd Majid, M.Z., Yousefpour, A., Mardani, A., 2020. Green efforts to link the economy and infrastructure strategies in the context of sustainable development. Energy 193, 116759.

Labib, S.M., Lindley, S., Huck, J.J., 2020. Spatial dimensions of the influence of urban green-blue spaces on human health: a systematic review. Environ. Res. 180, 108869.

Leigh, C., Burford, M., Connolly, R., Olley, J., Saeck, E., Sheldon, F., Smart, J., Bunn, S., 2013. Science to support management of receiving waters in an event-driven ecosystem: from land to river to sea. Water 5, 780.

Levy, S., 2015. The ecology of artificial wetlands. Bioscience 65, 346–352.

Locke, D.H., McPhearson, T., 2018. Urban areas do provide ecosystem services. Front. Ecol. Environ. 16, 203–205.

Lovelock, C.E., Accad, A., Dowling, R.M., Duke, N., Yip, S., 2019. Mangroves and saltmarshes of Moreton Bay. Moreton Bay Quandamooka & Catchment. 299.

Lundholm, J., 2015. The ecology and evolution of constructed ecosystems as green infrastructure. Front. Ecol. Evol. 3, 106.

MA, 2003. Millennium Ecosystem Assessment: Strengthening Capacity to Manage Ecosystems Sustainably for Human Well-being. World Resources Institute.

Malaviya, P., Singh, A., 2012. Constructed wetlands for management of urban stormwater runoff. Crit. Rev. Environ. Sci. Technol. 42, 2153–2214.

Maron, M., Ives, C.D., Kujala, H., Bull, J.W., Maseyk, F.J., Bekessy, S., Gordon, A., Watson, J.E., Lentini, P.E., Gibbons, P., 2016. Taming a wicked problem: resolving controversies in biodiversity offsetting. Bioscience 66, 489–498.

McInnes, K.L., Walsh, K.J.E., Hubbert, G.D., Beer, T., 2003. Impact of sea-level rise and storm surges on a coastal community. Nat. Hazards 30, 187–207.

Moore, T., Moloney, S., Hurley, J., Doyon, A., 2017. Implementing sustainability in the built environment: An analysis of the role and effectiveness of the building and planning system in delivering sustainable cities. Centre for Urban Research, RMIT University, Melbourne, Australia.

Needles, L.A., Lester, S.E., Ambrose, R., Andren, A., Beyeler, M., Connor, M.S., Eckman, J.E., Costa-Pierce, B.A., Gaines, S.D., Lafferty, K.D., Lenihan, H.S., Parrish, J., Peterson, M.S., Scaroni, A.E., Weis, J.S., Wendt, D.E., 2015. Managing bay and estuarine ecosystems for multiple services. Estuar. Coasts 38, 35–48.

Pataki, D.E., Carreiro, M.M., Cherrier, J., Grulke, N.E., Jennings, V., Pincetl, S., Pouyat, R.V., Whitlow, T.H., Zipperer, W.C., 2011. Coupling biogeochemical cycles in urban environments: ecosystem services, green solutions, and misconceptions. Front. Ecol. Environ. 9, 27–36.

Pauleit, S., Ambrose-Oji, B., Andersson, E., Anton, B., Buijs, A., Haase, D., Elands, B., Hansen, R., Kowarik, I., Kronenberg, J., 2019. Advancing urban green infrastructure in Europe: outcomes and reflections from the GREEN SURGE project. Urban For. Urban Green. 40, 4–16.

PFGGBG, 2016. Programa de Fortalecimento da Governança e da Gestão da Baía de Guanabara. PRA-BAÍA: PLANO DE RECUPERAÇÃO AMBIENTAL DA BAÍA DE GUANABARA.

Rogers, K., Boon, P.I., Branigan, S., Duke, N.C., Field, C.D., Fitzsimons, J.A., Kirkman, H., Mackenzie, J.R., Saintilan, N., 2016. The state of legislation and policy protecting Australia's mangrove and salt marsh and their ecosystem services. Mar. Policy 72, 139–155.

Roy, S., Byrne, J., Pickering, C., 2012. A systematic quantitative review of urban tree benefits, costs, and assessment methods across cities in different climatic zones. Urban For. Urban Green. 11, 351–363.

Russell, R.C., 1999. Constructed wetlands and mosquitoes: health hazards and management options—an Australian perspective. Ecol. Eng. 12, 107–124.

Schröter, M., Zanden, E.H., Oudenhoven, A.P.E., Remme, R.P., Serna-Chavez, H.M., Groot, R.S., Opdam, P., 2014. Ecosystem services as a contested concept: a synthesis of critique and counter-arguments. Conserv. Lett. 7, 514–523.

Sievers, M., Parris, K.M., Swearer, S.E., Hale, R., 2018. Stormwater wetlands can function as ecological traps for urban frogs. Ecol. Appl. 28, 1106–1115.

Sklar, F.H., Browder, J.A., 1998. Coastal environmental impacts brought about by alterations to freshwater flow in the Gulf of Mexico. Environ. Manag. 22, 547–562.

Sonter, L., Tomsett, N., Wu, D., Maron, M., 2017. Biodiversity offsetting in dynamic landscapes: influence of regulatory context and counterfactual assumptions on achievement of no net loss. Biol. Conserv. 206, 314–319.

Tan, J., Zheng, Y., Tang, X., Guo, C., Li, L., Song, G., Zhen, X., Yuan, D., Kalkstein, A.J., Li, F., Chen, H., 2010. The urban heat island and its impact on heat waves and human health in Shanghai. Int. J. Biometeorol. 54, 75–84.

Tan, P.Y., Zhang, J., Masoudi, M., Alemu, J.B., Edwards, P.J., Grêt-Regamey, A., Richards, D.R., Saunders, J., Song, X.P., Wong, L.W., 2020. A conceptual framework to untangle the concept of urban ecosystem services. Landsc. Urban Plan. 200, 103837.

Tan, B.A., Gaw, L.Y.-F., Masoudi, M., Richards, D.R., 2021. Nature-based solutions for urban sustainability: an ecosystem services assessment of plans for Singapore's first "Forest town". Front. Environ. Sci. 9, 610155.

Threlfall, C.G., Marzinelli, E.M., Ossola, A., Bugnot, A.B., Bishop, M.J., Lowe, E.C., Imberger, S.J., Myers, S., Steinberg, P.D., Dafforn, K.A., 2021. Toward cross-realm management of coastal urban ecosystems. Front. Ecol. Environ. 19, 225–233.

Tippler, C., Wright, I.A., Hanlon, A., 2012. Is catchment imperviousness a keystone factor degrading urban waterways? A case study from a partly urbanised catchment (Georges River, south-eastern Australia). Water Air Soil Pollut. 223, 5331–5344.

UN, 2015. World Urbanization Prospects. United Nations Population Division, United Nations, New York 2006.

Vallecillo, S., Polce, C., Barbosa, A., Perpiña Castillo, C., Vandecasteele, I., Rusch, G.M., Maes, J., 2018. Spatial alternatives for green infrastructure planning across the EU: an ecosystem service perspective. Landsc. Urban Plan. 174, 41–54.

Van Helden, B.E., Close, P.G., Steven, R., 2020. Mammal conservation in a changing world: can urban gardens play a role? Urban Ecosyst. 1–13.

Vico, G., Revelli, R., Porporato, A., 2014. Ecohydrology of street trees: design and irrigation requirements for sustainable water use. Ecohydrology 7, 508–523.

VictorianGovernment, 2020. Draft Yarra strategic plan. L. Department of Environment, Water and Planning, Australia.

Vijayaraghavan, K., 2016. Green roofs: a critical review on the role of components, benefits, limitations and trends. Renew. Sust. Energ. Rev. 57, 740–752.

Watson, J.E.M., Evans, T., Venter, O., Williams, B., Tulloch, A., Stewart, C., Thompson, I., Ray, J.C., Murray, K., Salazar, A., McAlpine, C., Potapov, P., Walston, J., Robinson, J.G., Painter, M., Wilkie, D., Filardi, C., Laurance, W.F., Houghton, R.A., Maxwell, S., Grantham, H., Samper, C., Wang, S., Laestadius, L., Runting, R.K., Silva-Chávez, G.A., Ervin, J., Lindenmayer, D., 2018. The exceptional value of intact forest ecosystems. Nat. Ecol. Evol. 2, 599–610.

Waycott, M., Duarte, C.M., Carruthers, T.J.B., Orth, R.J., Dennison, W.C., Olyarnik, S., Calladine, A., Fourqurean, J.W., Heck, K.L., Hughes, A.R., Kendrick, G.A., Kenworthy, W.J., Short, F.T., Williams, S.L., 2009. Accelerating loss of seagrasses across the globe threatens coastal ecosystems. 106, pp. 12377–12381.

WEPA, 2012. Outlook on Water environmental management in Asia 2012. Water Environment Partnership in Asia, Japan.

Whiting, G.J., Chanton, J.P., 2001. Greenhouse carbon balance of wetlands: methane emission versus carbon sequestration. Tellus B 53, 521–528.

Wotherspoon, D., Burgin, S., 2009. The consultant ecologist's role in the New South Wales (Australia) approach to biodiversity offsets: "BioBanking". Local Environ. 14, 61–71.

Ziter, C., 2016. The biodiversity–ecosystem service relationship in urban areas: a quantitative review. Oikos 125, 761–768.