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Publication date:
2020-08

Permanent link:
https://doi.org/10.3929/ethz-b-000412464

Originally published in:
Landscape and Urban Planning 200, https://doi.org/10.1016/j.landurbplan.2020.103837

Landscape and Urban Planning 200 (2020) 103837

Contents lists available at ScienceDirect

Landscape and Urban Planning

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

A conceptual framework to untangle the concept of urban ecosystem services

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ABSTRACT

Urban ecosystem service (UES) is becoming an influential concept to guide the planning, design, and management of urban landscapes towards urban sustainability. However, its use is hindered by definitional ambiguity, and the conceptual bases underpinning its application remain weak. This is exemplified by two different but equally valid interpretations of UES: "urban *ecosystem services*", referring to ecosystem services from analogs of natural and semi-natural ecosystems within urban boundaries, and "*urban ecosystem* services", a much broader term that includes the former group as well as urban services in a city. While we recognize that a single definition of UES is not possible nor necessary as its application is context-dependent, it is nevertheless useful to clarify the relationships between these interpretations to promote consistent use, and importantly, explore how a broader interpretation of UES might advance its applications in areas that have been neglected. We developed a conceptual framework that links UES to natural and human-derived capital to explain the relationships between the dual meanings of UES and proposed three normative propositions to guide its application: (1) integrate holistically multiple components of natural capital to provide UES, (2) reduce dependence on non-renewable abiotic resources and human-derived capital, and (3) enhance UES through technology. The framework we developed helps to resolve the current ambiguity in the meanings of UES, highlights the need to recognise neglected aspects of natural capital important for UES, and can be used to clarify relationships with related concepts conveying dependence of human well-being on nature.

1. Introduction

The landscapes of urban settlements comprise a large diversity of human-dominated areas that are shaped simultaneously by the interactions of cultural and natural factors (Tan, Liao, & Chan, 2018, 22). They are characterized by a high level of heterogeneity of spatial forms and extent, culture, and economic activities, and embed to varying degrees, natural and semi-natural spaces such as woodlands, wetlands, parks and other green spaces amidst the built environment. As the predominant habitat for the majority of the world's population, they deservedly receive significant attention in their planning, design and management (Ahern, 2013; Andersson, 2006; Borgström, Elmqvist, Angelstam, & Alfsen-Norodom, 2006). In this context, a concept that has been increasingly used to guide the planning and design of urban landscapes is "urban ecosystem services" (UES). Recent reviews on UES (e.g., see Haase et al., 2014; Luederitz et al., 2015) underscore its use in diverse disciplines, connected by an overarching goal of shaping urban landscapes to be more sustainable and liveable.

UES is appealing as a concept to promote urban sustainability for several reasons. First, there is a direct analogy to the established and popular concept of "ecosystem services". Ecosystem services highlight human dependence on natural ecosystems for our well-being. Similarly, UES reinforces the idea that ecosystems services can be locally produced in urban areas to support human well-being in tangible and intangible ways. Second, urbanization worldwide leads to a general dissociation of urban dwellers from nature (Turner, Nakamura, & Dinetti, 2004). Such an "extinction of experience" of nature may have adverse consequences on the attitudes and behavior of urban dwellers toward

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https://doi.org/10.1016/j.landurbplan.2020.103837
Received 18 September 2019; Received in revised form 18 April 2020; Accepted 21 April 2020
Available online 27 April 2020
0169-2046/

environment stewardship and urban sustainability (Ives et al., 2017; Soga & Gaston, 2016). Natural ecosystems in cities provide opportunities for urban dwellers to experience nature and engage in stewardship of the environment (Andersson et al., 2014), and UES serves as a conceptual tool to reinforce this goal. Third, in extending the use of UES as a conceptual tool for environmental stewardship, UES also acts as a social tool to bring together diverse stakeholders to foster community-driven (Luederitz et al., 2015) and government-led planning (Rall, Kabisch, & Hansen, 2015) for urban sustainability.

Despite its increasing usage, what constitutes an UES is still ambiguous. The first reason for this is inconsistencies in how the term "service" is interpreted, and particularly in how this term relates to the concepts of "processes", "functions" and "benefits". Multiple definitions exist, and various scholars have discussed the differences among them and the need to use the term more consistently (see Fisher, Turner, & Morling, 2009; La Notte et al., 2017; Nahlik, Kentula, Fennessy, & Landers, 2012), which we do not repeat here. In this paper, we focus on the second reason, which arises from the dual meanings of "urban ecosystem". This term is commonly used to refer to natural, semi-natural, or managed communities of organisms and habitats that lie within urban boundaries. These include remnant, relatively undisturbed vegetated areas (e.g., such as forest patches and riparian corridors), as well as highly managed urban green spaces such as parks and gardens. Increasingly, this definition is also extended to include greenery on buildings and infrastructure such as green roofs and green walls. The second, more expansive use of "urban ecosystem" refers to the entire city as a human-dominated ecosystem. This latter usage can be traced back to the 1960s, when ecologists began to conceive of cities as ecosystems, and adopt a "systems perspective" to understand them (Alberti, 2007, 9). The definition of a city as an ecosystem is now prevalent in the urban ecology and urban system science literature (for example, see Alberti, 2007; Decker, Elliott, Smith, Blake, & Rowland, 2000; Grimm et al., 2008; Pickett & Grove, 2009). It follows from the two meanings of urban ecosystem that there are two possible literal interpretations of UES: "urban *ecosystem services*", referring to the ecosystem services which are produced from natural or semi-natural spaces within urban boundaries, and "*urban ecosystem* services" which are the services in, of, or pertaining to cities as urban ecosystems. The first interpretation is in most common use in the UES literature, and deals with the natural and semi-natural spaces within cities (Luederitz et al., 2015). The second interpretation could be considered to cover not just ecosystem services from natural ecosystems as applied in the former definition, but also the wide range of services produced by humans, including housing, transport, education, entertainment, or medical care—in fact to any service relating to urban areas that is needed by urban dwellers. We refer to this latter group of services as "urban services", following Antognelli and Vizzari (2016) and Belanche, Casaló, and Orús (2016). Specifically, Antognelli and Vizzari (2016) used urban services to refer to "basic provisions such as sanitary sewer systems, domestic water systems, fire and police protection services, public transit services, road construction services, lighting systems, recreational facilities, schools". "*Urban ecosystem* service" thus reflects a broad perspective, including services from natural ecosystems and urban services, and which may be deemed as UES *sensu lato*. "Urban *ecosystem services*" more narrowly refers to services generated from natural ecosystems and is UES *sensu stricto*. For clarity, we henceforth use "ecosystem services in urban areas" to denote urban *ecosystem services,* and "services of urban ecosystems" to denote *urban ecosystem* services in this article. Table 1 highlights the key differences between these two interpretations of UES.

We can trace the conceptual ambiguity in these two to two influential papers on UES. In the first, Bolund and Hunhammer wrote: "In the case of the urban environment, it is both possible to define the city as one ecosystem or to see the city as composed of several individual ecosystems …", but for simplicity, they chose to define the term urban ecosystems as all "natural green and blue areas in the city" (Bolund & Hunhammar, 1999, 24). One might infer from this that these individual ecosystems are implied to be smaller ecosystems nested within the city as a larger ecosystem, and accordingly, the ecosystem services produced within smaller ecosystems are a subset of those from the city as an ecosystem. However, exactly which services might be included in the latter category was not elaborated (Bolund & Hunhammar, 1999). In the second influential report on the topic, the Millennium Ecosystem Assessment highlighted that there are several perspectives that might be taken in the interpretation of UES in posing this question: "ecosystems in urban systems, urban systems as ecosystems, or ecosystems and urban systems?" (MEA, 2005, 799). The first term is akin to the concept of "ecology *in* city", the second to "ecology *of* city", paradigms which originated from the pioneering work of Grimm, Grove, Pickett, and Redman (2000) and Pickett (2001) on cities as urban ecological systems. The third option in MEA's question presumably implies a separation between natural ecosystems and the built components of cities. The MEA took the position that it does not "treat all urban services as ecosystem services", as ecosystems are "understood to be biophysical systems" and thus ecosystem services from urban systems are "assumed to be distinct from the value internally added through the application of human labor [and other capital]" (ibid). Bolund and Hunhammar (1999) and MEA (2005) were thus specific in defining which ecosystems produce "ecosystem services". While they have adopted the narrower interpretation of UES, however, the two contrasting notions of UES described above are equally valid and equally supported by their own literatures and research communities. Much less has been written about the broader concept of UES, i.e., services of urban ecosystems, and the value of this concept has not been discussed in detail.

Concepts and frameworks are important because they shape the types of questions that scientists ask (Amundson & Jenny, 1997). Definitions of terms, therefore, have importance beyond semantics. Golubiewski (2012) suggests that "using inappropriate rhetoric misdirects researchers, which influences scientific investigation—from problem statements to interpretations". Thus, the specific ways in which commonly used but ambiguous terms with broad meanings, such as "ecosystem services", "sustainability" and "resilience" are used as metaphors are thus important, as how they frame the environment can promote or restrict discourse on environmental management and influence the political significance of the subject matter. For instance, Coffey (2016) argued that the dominant use of ecosystem services as an economic metaphor risks creating a narrow, anthropocentric perspective of the environment, as it places excessive emphasis upon the provision of goods and services of value to humans. As also highlighted by Polasky, Tallis, and Reyers (2015), a lack of common understanding and definition in ecosystem services research is also a barrier to translating research outcomes to action for practitioners and policy makers. To encourage accurate applications, it is necessary to unpack multiple meanings of terms. For instance, Mace, Norris, and Fitter (2012) illustrated the value of doing this for the term "biodiversity", a commonly used term that is beset with unclear, overlapping applications.

Against this background, it is important to untangle the two starkly contrasting meanings of UES and develop a conceptual basis for distinguishing between them. Given the increasing use of the term UES in research, in policy documents and by the media, a clarification of the differing conceptions is urgently needed. In this perspective paper, we introduce a definition of UES as "aspects of ecosystems that are generated from natural capital in combination with human-derived capital, and that contribute, directly or indirectly, to human well-being in urban areas", which we believe adequately captures both interpretations of UES. Natural capital as used here refers to the biotic and abiotic components of natural ecosystems, from which ecosystem services are produced for human well-being (Gray, 2018; Guerry et al., 2015; Smith et al., 2017). The relationship between natural capital and ecosystem services is further discussed in Section 3.1.

The aim of this article is to promote a greater understanding of the

Table 1
Interpretations of "urban ecosystem services". The classification of provisioning, regulating, supporting and cultural ecosystem services follows MEA (2005). The classification of services of urban ecosystems follows Antognelli and Vizzari (2016), with additional examples added by the authors.

Urban Ecosystem Services		
	"ecosystem services in urban areas"	"services of urban ecosystems"
Definition	ecosystem services as conventionally used and which are produced from natural or semi-natural spaces within urban boundaries	services in, of, or pertaining to cities as urban ecosystems
Alternative descriptions	• urban *ecosystem services* • urban ecosystem services *sensu stricto*	• *urban ecosystem* services • urban ecosystem services *sensu lato*
Types of ecosystem services	• Provisioning ecosystem services, such as production of fresh produce, and harvesting of storm water for reuse, etc, • Regulating ecosystem services, such as control of stormwater discharge, mitigation of heat in urban areas, mitigation of noise, etc. • Supporting ecosystem services, such as provision of habitats for urban biodiversity, provision of pollinators for urban farms, etc. • Cultural ecosystem services, such as urban landscapes promoting sense of place and social relations, provision of education and recreational services, etc.	• Provisioning services, covering ecosystem services from natural ecosystems, and services such as provisioning and distribution of energy, water and food through infrastructure networks • Regulating services, covering ecosystem services from natural ecosystems, and services such as waste and waste-water collection systems and treatment plants, indoor climate regulation, use of noise barriers, use of seawalls for coastal protection, concrete channels for stormwater discharge, etc. • Social services, such as transportation networks, educational services and healthcare services • Cultural services, covering ecosystem services from natural ecosystems, and services such as museums, theatres, conserved monuments and buildings, entertainment and recreation services, etc.

contrasting meanings of UES and their use, so that landscape and urban planning can consider a broad spectrum of ecologically based urban services that can better contribute to urban sustainability. Specifically, we focus on three areas: (1) What are the trends in use of UES in the published literature? (2) What do UES refer to in the literature? (3) How might a broader framing of UES be used to advance our understanding of the provision of UES in cities? In the following sections, we describe a literature review conducted to understand the definitions and use of the UES adopted in peer-reviewed studies. Through a conceptual framework in which we link UES to natural and human-derived capital, we explain the foundations for proposing that urban services are *bona fide* urban ecosystem services. We describe three normative propositions on how the framework can be used to guide provision of UES through a better understanding of its potential and limitations. We conclude with recommendations on further work that is needed to address key questions that may arise from the application of our framework.

2. Use of the term "urban ecosystem services"

To understand how the term UES has been used, we searched ISI Web of Science for all papers published over two decades between 1999 and 2018. We focused on the trends in, and meanings implied by its use, and the types of ecosystems considered. As UES is increasingly linked to related but relatively newer concepts, namely "green infrastructure" and "nature-based solutions" (Chenoweth et al., 2018; Escobedo, Giannico, Jim, Sanesi, & Lafortezza, 2018), we also compared publications on UES to these terms. We retrieved a total of 319 articles on urban ecosystem services, 4090 on ecosystems services, 150 on green infrastructure, and 18 on nature-based solutions. The cumulative number of articles published over the past two decades is shown in Fig. 1 (details in Supplementary Materials 1).

2.1. Trends in use of terms

We highlight four key trends from this review. First, although the number of papers on UES was only a small fraction of those on ecosystem services (ES), the average annual increase in publications over the past decade was substantially higher for UES than for ecosystem services (57% compared to 32%, respectively; data not shown), reinforcing our earlier point on its increasing use as scholars turn their attention to urban areas. On a yearly basis, there were more papers related to UES than to green infrastructure and nature-based solutions.

Second, about half of the 319 papers reviewed on UES provided no

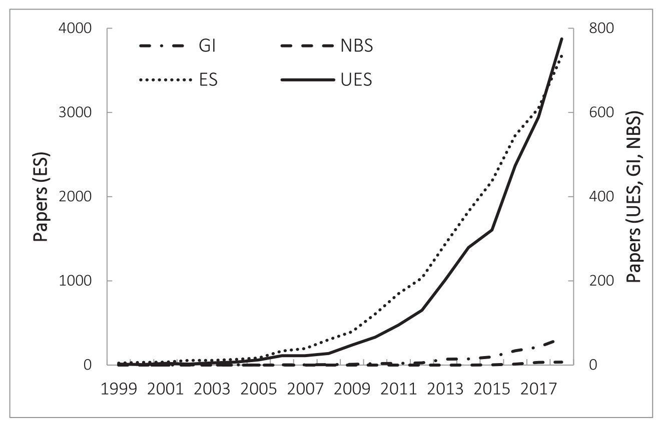

Fig. 1. Cumulative number of papers with "ecosystem services" (ES), "urban ecosystem services" (UES), "green infrastructure" (GI), "nature-based solutions" (NBS) in title, abstract or keywords. Note the different y-axis for ES. Details on literature search are in Supplementary Materials 1.

definition of ecosystem services, while the remaining 166 papers used definitions derived from a selected few main sources listed in Supplementary Material 2. These source articles, however, are inconsistent in their interpretations of the word "service", emphasizing to different degrees, ecosystem services as benefits, ecological structures, and components, functions and processes of ecosystems, all of which have distinct ecological meanings. This definitional problem of UES remains unresolved as seen in the inconsistent use of UES in publications over the recent five years.

Third, UES were attributed to a large variety of urban land cover and land use types, of which the most frequently used were forest, cultivated land, urban greenery, parks, and urban trees (Fig. 2). A significant minority of publications also considered the ecosystem services provided by community gardens, allotment gardens, domestic gardens and rooftop gardens within urban areas. In more recent years, with the advent of green roofs and green walls, there are also several papers that examine the ecosystem services provided by these novel ecosystems. This diversity underscores the fact that the term "ecosystem" is not restricted to any specific spatial scale, and so there can be multiple urban ecosystems within any geographical location, depending on which boundary is used to define the ecosystem of interest, e.g. administrative boundary, watershed, a remnant woodland, etc. Which scale is most appropriate depends, therefore, on the study context, the research question posed, and the urban challenges to be addressed.

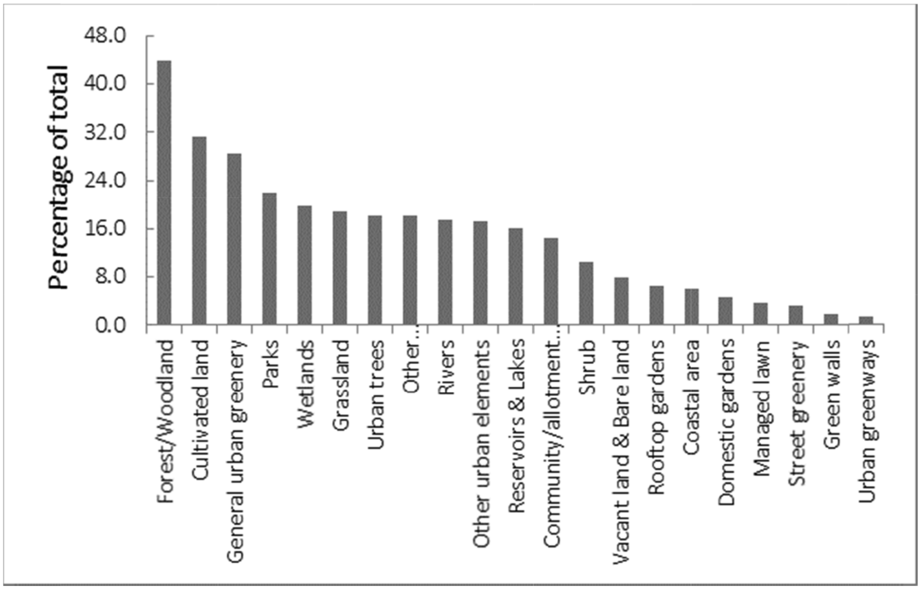

Fig. 2. Types of land use and land cover assessed in UES provision as percentage of total papers. "General urban greenery" refers to general managed and unmanaged green areas and vegetation in cities. "Other urban elements" refer to urban built-up areas with elements such as impervious or semi-pervious surface, artificial structures, construction land, and grey infrastructure. Please see specific definitions of terms in Supplementary Materials 3.

Accordingly, different types of UES are produced depending on which scale is applied to an urban ecosystem.

Fourth, the term "urban ecosystem" may refer to one of two distinct perspectives: that of diverse natural elements within the urban area, or of the entire urban system including the natural and built or abiotic components. However, the overwhelming majority of UES publications takes the first perspective, treating urban ecosystems to be natural and semi-natural areas within or adjacent to urban areas. Only a few papers assessed UES derived from the abiotic components of cities. For instance, Kroll, Müller, Haase, and Fohrer (2012) assessed the potential of the abiotic components of the environment to provide renewable energy from wind, water and solar radiation, as well as non-renewable materials such as lignite, as types of provisioning ecosystem services to support the energy demand of an urban settlement. Yang et al. (2015) assessed the stock of industrial land as a source of ecosystem service in the manufacture of goods in urban agglomerations in China. Morel, Chenu, and Lorenz (2015) argued that the soil, even in urban or built-up sites, is a neglected abiotic resource that is capable of providing a wide range of ecosystem services, and called for better consideration of soils in urban planning and management. Tiwary and Kumar (2014) also highlighted the need to consider not just green infrastructure, but also its interaction with grey infrastructure for assessment of UES. These examples are the exceptions, however, in a literature that is focused predominantly upon more natural habitats in cities. This emphasis reflects the lasting influence of the earliest publications on UES, in which urban ecosystems was used to denote constructed wetlands, riparian corridors, urban parks (Cairns & Palmer, 1995), urban forests (Freedman, Love, & O'Neil, 1996), and "all natural green and blue areas in the city, including … street trees and ponds" (Bolund & Hunhammar, 1999). This influence may also be seen in recent reviews on UES (Table 2), all of which defined or implied UES as provided by urban analogs of natural ecosystems.

We conclude that, as a relatively new term, UES is used to refer to a very wide range of benefits provided mainly by a diverse range of urban elements covering natural ecosystems, constructed ecosystems, and to a limited extent, the abiotic components of cities. Importantly, we find little theoretical basis or conceptual underpinnings to support such a broadly-based application of UES. Like ecosystem services, which has been described as a catch-all phrase that refers to anything in an urban landscape beneficial to humans (Nahlik et al., 2012), UES is similarly used in a loose way to convey their importance in urban areas. It appears that UES has been conceived by directly transplanting the ecosystem services concept to urban areas, but unlike the latter which has been, and continues to be strengthened by numerous conceptual approaches, the conceptual framing of UES remains weak. We address this gap using a conceptual framework linking UES to the concept of natural and human-derived capital.

3. A conceptual framework for broadening our understanding of urban ecosystem services

We are not alone in attempting to reconcile the different interpretations of UES. Grimm and Cook (2015) posed what they called the "ecosystem conundrum", asking "if cities are ecosystems, as urban ecologists have argued, then are not all services they provide 'ecosystem services'?". The authors have also argued that cities should be more comprehensively treated as "social-ecological-technological systems", but questioned the usefulness of UES as a concept that applies generically to all facets of a complex social-ecological-technological system, which would include such systems such as public transportation and wastewater treatment plants. Therein lies the conundrum: an all-inclusive definition of urban ecosystem services as all urban services fails to recognize the merits of ecosystem services as a concept that highlights human dependence not only on engineered systems but also on natural ecosystems. Grimm et al. (ibid) proposed that services can arise from the built, natural and hybrid (built and natural) systems, and called for an expanded framing to describe the diversity of services, and their use for human benefits.

More recently, Beichler et al. (2017) provided a detailed analysis of the urban ecosystem service concept in relation to the types of urban systems or structures that may provide these services. The authors suggested that all urban structures, which they classified into four broad categories ("natural", "managed", "overbuilt" and "constructed"), can, in principle, be considered as providing ecosystem services for urban dwellers. However, they argued that two additional factors should be considered: the extent of human input, including modification of the ecosystem in ensuring that services can be provided, and whether or not in so doing, the "normative principle" in the use of ecosystem services as a boundary concept to promote nature conservation is compromised. In other words, if we treat the services provided by artificial urban structures as equivalent to those from natural systems, we might undermine the unique contribution of natural systems and thereby challenge the application of the ecosystem services concept to urban areas.

We suggest that both the narrower (ecosystem services in urban areas) and more expansive (services of urban ecosystems)

Table 2
Definition of the "ecosystem" relating to "urban ecosystem services" in recent review and synthesis articles.

Paper	Definition of "Urban Ecosystem Services"	Definition of "Ecosystem"
Grunewald and Olaf (2017)	Not directly defined. Reference to services from ecosystem services from "internal urban ecosystems", which are the "direct and indirect contributions of nature to human well-being"	"Urban ecosystems are mainly represented by different types of green spaces in the city…. This includes particular parks, urban forests, cemeteries, vacant lots, gardens and yards, landfills as well as road trees, green roofs, and walls. Blue infrastructure (urban water ecosystems) such as streams, lakes, ponds, artificial swales, and storm water retention ponds is part of the green infrastructure"
Luederitz et al. (2015)	"those services that are directly produced by ecological structures within urban areas, or peri-urban regions"	"ecological structures" in papers reviewed, such as forests, river/ streams, cultivated land, rooftops, coastal areas
Haase (2015)	"ES are the subset of ecological functions (physical, chemical, and biological processes) that are directly relevant or beneficial to human well-being". This definition is presumably extended to ecosystems in urban areas.	"Urban ecosystems, such as wetlands, forests, parks, and estuaries, …" and "UES are generated by a diverse set of land uses, including parks, cemeteries, golf courses, avenues, gardens and yards, verges, commons, green roofs and facades, sports fields, vacant lots, industrial sites, and landfills"
Andersson et al. (2014)	Not defined. Reference made to natural terrestrial and marine systems to generate ecosystem services.	Not defined, but reference made services generated by green infrastructure and urban green spaces.
Gaston, Ávila-Jiménez, and Edmondson (2013)	Not defined. Reference made to ecosystems covered by areal extent of urban areas.	Not defined. Reference made to green spaces in urban areas as the main source of ecosystem goods and services.
Gómez-Baggethun and Barton (2013)	"defined here as those [services] provided by urban ecosystems and their components"	"Urban ecosystems are those where the built infrastructure covers a large proportion of the land surface, or those in which people live at high densities …They include all 'green and blue spaces' in urban areas, including parks, cemeteries, yards and gardens, urban allotments, urban forests, wetlands, rivers, lakes and ponds"; "…urban ecosystems are often portrayed as 'green infrastructure' …"; "Urban ecosystems may be seen as a broader concept …can also include community-driven forest or river/ lake areas close or within the city boundaries as well as private gardens …"

interpretations of UES can find applications under a wide range of contexts. However, the conceptual basis and the value of taking the expanded notion of UES remains obscure to-date. We propose a conceptual framework that seeks to clarify the relationships between the two interpretations of UES and provide the foundations for adopting a broader interpretation of UES. This framework may also be valuable in clarifying the relationships between UES and related concepts.

3.1. Key premises of framework

Our framework is grounded on the view of cities as urban ecosystems, more recently characterized as a socio-ecological-technological system (Grimm & Cook, 2015; McPhearson et al., 2016) (Fig. 3). Within the urban ecosystem, human well-being is dependent on a wide range of services; some of these are provided mainly by natural and semi-natural ecosystems, such as recreation in green open spaces and fresh food from urban aquaculture, while others, such as housing, transport, health, education and telecommunication, are created by humans. In our framework, all these services can be defined as "services of urban ecosystems" (Table 1). We explain in this section the conceptual underpinnings of this interpretation.

The first term to be defined is "service". As earlier highlighted, there are large differences in how this term is used in the context of ecosystem services (see La Notte et al., 2017; Nahlik et al., 2012). Following Fisher et al. (2009), we refer to services as the aspects of ecosystems used actively or passively to support human well-being. These aspects, in turn, have two components—"structures" and "processes"—with structures referring to the social, ecological, and technological components of cities, and processes to the flows of materials, energy, and information occurring between and within these components. Such a definition is based on the perspective there is a structure and process relationship in cities that determines urban functions (Alberti, 2007).

UES are derived from stocks and flows of natural capital, but the realization of ecosystem services is also reliant on other forms of capital, broadly termed as "human-derived capital". Constanza describes this clearly in saying that ecosystem services "refer to the relative contribution of natural capital to the production of various human benefits, in combination with the three other forms of capital" (Costanza, 2012, 27). He highlights that in order for ecosystem services from natural capital to be fully realized, natural capital has to be combined with other forms of capital. This is particularly true for UES. For instance, an urban park cannot exist without financial capital and input of human capital, at all stages from design to construction to maintenance; green roofs and green walls use substantial amounts of construction materials, like drainage cells, geotextile and supporting structures made of steel, concrete, plastics, etc.; coastal defenses can only be constructed with human and built capital, even when they rely heavily on natural ecosystems such as wetlands. UES could thus be conceived as being produced through a combination of natural and human-derived capital, with some requiring more of the former and less of the latter, and *vice-versa*. Such a combination could be represented by a gradient, as shown in Fig. 3.

"Natural capital", like ecosystem services, also has many definitions. The most widely used definition refers to the biotic and abiotic components of natural ecosystems from which ecosystem services are produced for human well-being (Gray, 2018; Guerry et al., 2015; Smith et al., 2017). As an economic metaphor, the capacity of natural capital to generate ecosystem services also invokes the use of "stocks and flows", in which stocks refer to amounts of natural capital, flows refer to transformation or movement of the stocks, and ecosystem services are derived from both the stocks and flows of natural capital (Jones et al., 2016). The biotic component comprises all living organisms and can be considered at different hierarchical levels from the individual, community and population; the abiotic component comprises non-living resources such as minerals, earth materials (e.g. sand, silt, sediments), fossil fuel, etc. Within an ecosystem, there are also abiotic processes, which refer to flows of energy and materials driven by energy systems from the sun, moon (tidal), geology (e.g. geo-thermal) and hydrological systems occurring within the atmospheric terrestrial and aquatic components of the biosphere. Abiotic processes can exist independently of biotic structures, because they are part of large-scale processes on Earth, but it should be highlighted that within a natural ecosystem, flows of energy and materials are highly regulated by the

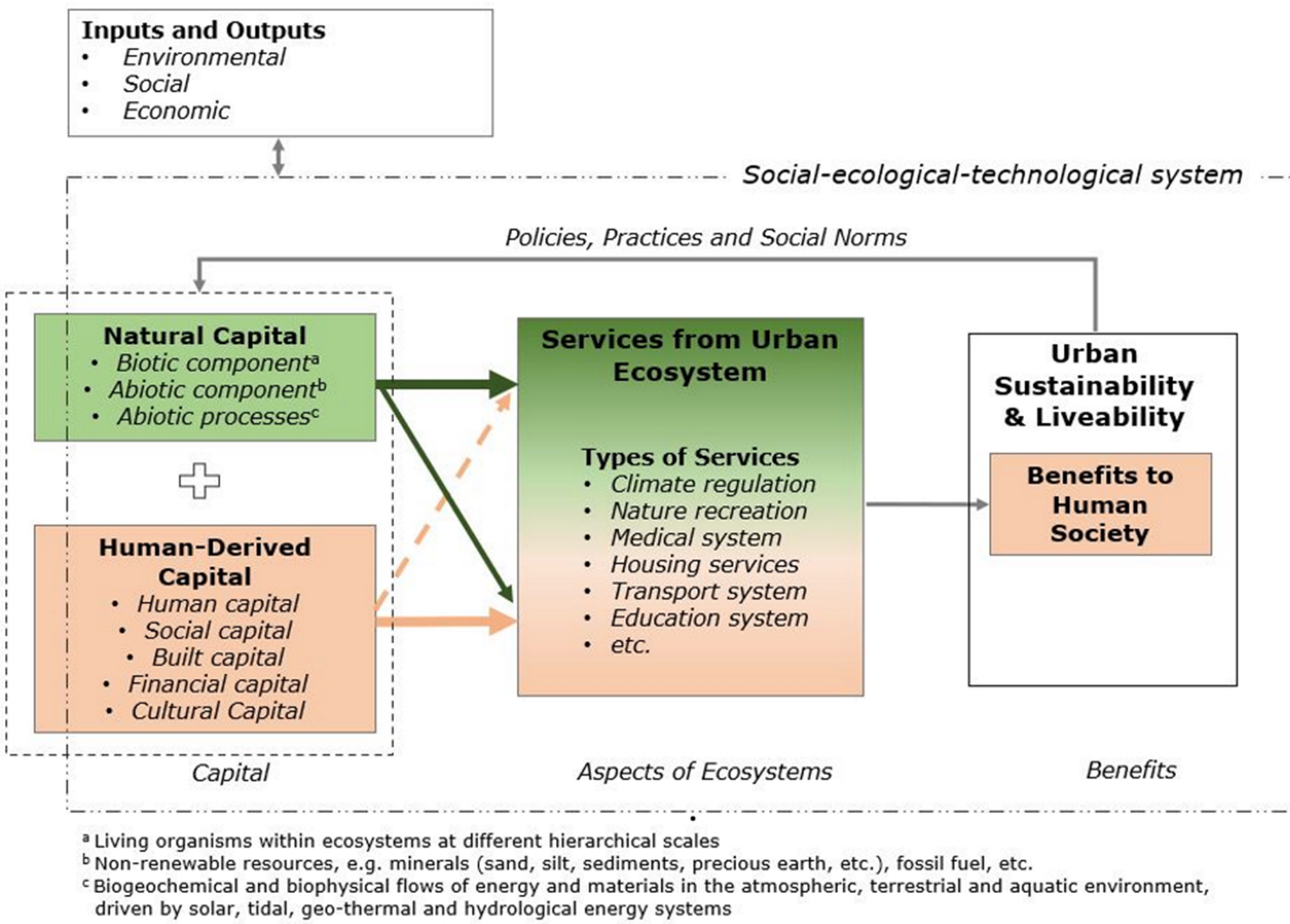

Fig. 3. Conceptual framework linking natural and human-derived capital to human well-being through the provision of services from urban ecosystems. The green arrows of different thickness represent varying levels of natural capital input to generated UES, and the beige arrows reflect input of human-derived capital. The dotted line indicates an indirect input, and solid line indicates a direct input. The colour gradient from green to beige denotes that UES is produced through a combination of capitals, and the extension of capital outside urban boundary indicates cross-scale flows of capitals to produce UES.

biotic component and therefore, they are biophysical and biogeochemical in nature. Nevertheless, despite it being a fundamental component of natural ecosystems, the abiotic component has generally been neglected in ecosystem services studies (Gray, 2018; van der Meulen, Braat, & Brils, 2016).

Human-derived capital (Jones et al., 2016) is of various types, including "produced capital" (built or manufactured capital such as roads, buildings, infrastructure), "human capital" (the productive capacity of human beings covering skills and knowledge), "social capital" (the stock of network and trust among humans and within social groups and communities), "cultural capital" (values and beliefs, and public and governance systems), and "financial capital" (money and financial assets that facilitate transactions between capital and social groups). As urban areas are also heavily reliant on resources from outside urban boundaries, the framework makes explicit this dependence on external input, as well as the socio-ecological drivers that impact the whole urban ecosystem (Pickett et al., 2013; Tan & Abdul Hamid, 2014).

According to our framework, the forms of capital needed to generate UES for human well-being have a hierarchical relationship to each other that is consistent with the Daly's Triangle (Fig. 4). According to this concept, natural capital is the "ultimate means" for achieving human well-being, which is the "ultimate end" (Meadows, 1998; Wu, 2013); other forms of capital are treated as "intermediate means" and "intermediate ends". This is because all forms of built capital, such as infrastructure and buildings, originate from natural capital, which is therefore the ultimate source of human well-being. Built infrastructure relies on extraction of abiotic resources such as minerals and earth materials, and is constructed or processed using energy, whether renewable or non-renewable, from abiotic processes of natural capital. For example, buildings are created from abiotic components such as sand, cement, timber, steel, polymers, and glass, and the heating and cooling needs of buildings are met by abiotic components and processes for energy generation. Similarly, telecommunication infrastructure has long depended on abiotic components. From cross-continental telegraphy's dependence on *gutta percha* and Indian rubber for insulating submarine cables in the mid-1800s to 1930s (Headrick, 1987), to the current internet era using fibre-optic submarine cables insulated with petroleum-based polymers, this essential service cannot be achieved without biotic and abiotic resources drawn from nature.

It should also be pointed out that flows from natural to human-derived capital are numerous and occur at different spatial scales, making it almost impossible to determine the relative contributions of different types of capital in generating UES. In an increasingly globalized economy, UES consumed within an urban boundary can be derived from natural and human-derived capital originating outside the urban area and its hinterland. The disruption of global supply chains, including food supply, by COVID-19 pandemic highlights vividly (Sohrabi et al., 2020), the dependence on, and vulnerabilities of urban areas to cross-scale movement of natural capital outside urban and natural boundaries. Human dependence on natural capital is total and absolute, which means that all urban services have their origins in natural capital. Therefore, urban services are urban ecosystem services.

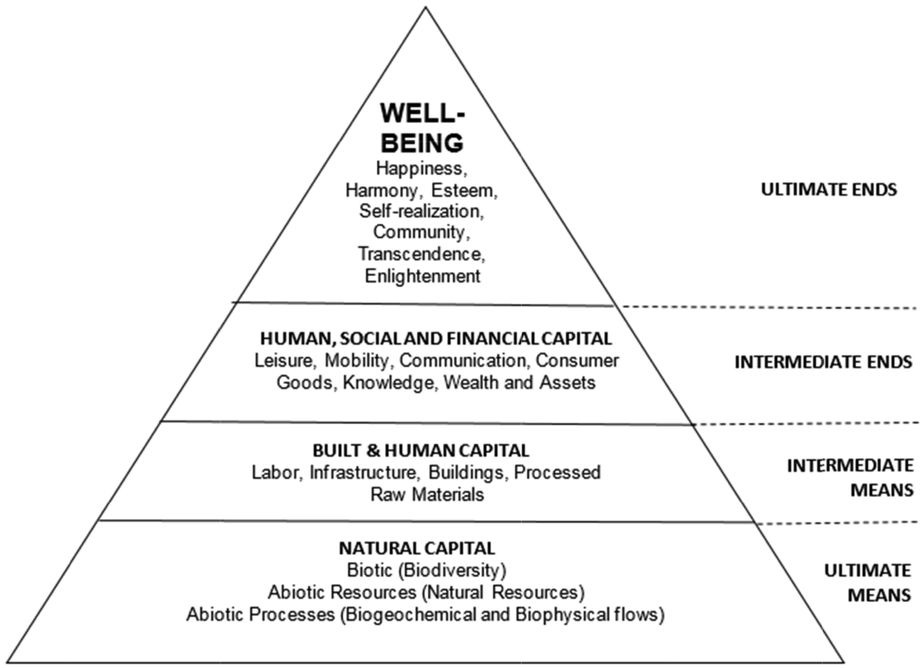

Fig. 4. The Daly's Triangle from Wu (2013) which relates ultimate human purpose to natural capital.

UES potentially produce benefits for humans. Due to the anthropocentric framing of the ecosystem services concept, numerous scholars have suggested that processes and functions from natural capital only generate a "service" if there are direct human beneficiaries of the service (Costanza, 2012; Fisher et al., 2009). This is contingent upon a demand for, and use of, ecosystem services which culminates in benefits for humans and societies. As there are feedback loops between the social and ecological components (Grimm et al., 2000), we also suggest in Fig. 3 that human demand and use of UES eventually dictates societal decision-making via policies, professional practices and societal norms. These in turn, influence the use of natural and human-derived capital to generate UES through a feedback loop.

In this context, we propose a definition for urban ecosystem services as "aspects of ecosystems that are generated from natural capital in combination with human-derived capital, and that contribute, directly or indirectly, to human well-being in urban areas". In this definition, we use "ecosystem" rather than "urban ecosystem" to reflect the cross-scale dependence on movement of natural capital, and aspects of human-derived capital to meet human needs in urban areas.

3.2. Propositions in using the conceptual framework

A definition of UES that includes all types of urban services is so broad that it covers both metaphorically and literally, "everything under the sun". Such a notion is potentially problematic, as highlighted by Grimm and Cook (2015). On the other hand, such breadth reflects an objective view of how things are, rather how they ought to be, using the analogy from the Herbert Simon's "The Sciences of the Artificial" (Simon, 1996). At this level, the framework represents a view of urban ecosystems as socio-ecological-technological systems, but is silent on how it can be used to advance societal goals with regards to how cities should be developed, such as for urban sustainability, a goal which is fundamentally normative in nature (Parnell, 2016). For instance, as cities expand their boundaries in response to growing populations, tradeoffs in land use are inevitable, such as between clearing its forests (natural capital), and creating land for housing and industries (built capital) with the aim of creating wealth for its citizens (human capital). Reduction of natural capital is not without adverse consequences, as loss of forested land can alter a city's hydrology and climate, leading to adverse consequences such as flash floods and the urban heat island effect. How should cities manage such tradeoffs? Similarly, should a city reclaim land from coastal or inland waters, that destroy aquatic habitats, remove protective coastal ecosystems against storms, and destroy livelihood of communities dependent on aquatic resources, but in the process create manufactured capital and financial capital for the city that are essential for economic progress? These are clearly difficult land use decisions that are wicked in nature.

The framework cannot adjudicate these matters. Rather, as an objective representation of a city's dependence upon both natural and human-derived capital, the use of this framework has to be guided by normative (and by implication, societal) goals, such as creating liveable and sustainable societies. We illustrate this using three normative propositions to highlight the implications of the framework on production of UES to meet societal goals.

(1) Holistically integrate multiple components of natural capital to provide UES

This proposition stems from two observations. The first is that current efforts to deliver ecosystem services are biased towards certain components of natural capital. For instance, Brilha, Gray, Pereira, and Pereira (2018) and Gray (2018) recently pointed out that ecosystem services studies usually pay insufficient attention to the abiotic component of natural capital, which they describe as "geodiversity", which comprises minerals, rocks, soils, water, physical and geochemical processes. They suggest that this neglect reflects a dominant focus in the ecosystem services literature on biotic nature, even though the concept of natural capital explicitly recognises both components. One consequence is to underestimate the full benefits from natural capital.

Ann Spirn also highlighted in her seminal book "The Granite Garden" more than 30 years ago that when appropriately harnessed, natural forces represent "a powerful resource for shaping a beneficial urban habitat", but "cities have mostly neglected and rarely exploited the natural forces within them" (Spirn, 1984, xi). She went on to recommend the use of biophysical and biogeochemical processes that pervade urban areas to guide urban design. We repeat her call here to take advantage of all components of natural capital in urban planning and design. For example, many cities have directed their attention to the use of vegetated areas to mitigate high urban temperatures, but a more comprehensive approach would include abiotic processes such as creating ventilation channels using urban morphology to direct wind flow, and abiotic components such as water bodies, shade cast by buildings, and building materials with high albedo that are able to better reflect solar radiation to combat urban warming. Similarly, instead of just focusing on the capacity of urban vegetation to mitigate air pollution, this critical urban challenge might be better tackled through the use of fuels that produce less emissions (abiotic component), wind channels that disperse pollutants (abiotic process), and physical barriers that separate humans from emission sources (abiotic component). The key emphasis is that urban challenges are best addressed holistically across disciplines and using approaches that combine biotic and abiotic components and processes, rather than focusing on any specific component alone.

The second point is related to the limitations of natural components in cities to address major urban challenges. There is a general misunderstanding of the extent and importance of the contributions of ecosystem services in urban areas (Pataki et al., 2011) which needs to be corrected. For instance, tree planting is often promoted by advocacy groups on the basis that urban trees combat climate change through carbon sequestration (see Kanniah, Muhamad, & Kang, 2014; Papa & Cooper, 2019). However, it was already pointed in an urban forest study in the US in 1993 (Nowak & McPherson, 1993) that planting 100 million trees will optimistically, only offset the carbon emission in the US by less than 1 percent over a 50-year period. More recent studies now also dispel the notion that carbon sequestration from urban vegetation can make significant offset to cities' carbon emission (Chen, 2015; Tang, Chen, & Zhao, 2016). Even if a whole city were cloaked in greenery, this would contribute only marginally to mitigating the local emission of greenhouse gases or changing atmospheric CO_2 concentration. New evidence now also shows that the role of urban vegetation to improve air quality may have also been over-estimated (Eisenman et al., 2019; Viippola et al., 2018; Whitlow, Pataki, Alberti, Pincetl, Setala, Cadenasso, Felson, & McComas, 2014). The limits of natural ecosystems in cities to in addressing key urban challenges is also imposed by the physical limitation of natural or semi-natural spaces in cities— cities are dominated by the built component (Tan & Abdul Hamid, 2014). Densifying cities usually face challenges in providing such spaces (Haaland & van den Bosch, 2015, Edwards, 2020). Thus, generation of UES to satisfy human needs cannot be dependent on the natural component alone.

The corollary of the above point that is that as we seek to use urban services to meet human needs—which draw on natural capital—it becomes even more crucial to conserve such natural capital outside urban boundaries of cities. In a globalized world that is heavily dependent upon the cross-scale movement of goods and resources, it is more necessary than ever to take a global rather than purely national or city-level approach to conserving natural capital.

(2) Reduce consumption of non-renewable abiotic resources and human-derived capital to produce UES

Even though our framework highlights that UES are derived in part from non-renewable resources, it does not suggest in any way that humans should, or indeed, can continue this path of resource over-extraction that is a fundamental cause of current environmental destruction. On the contrary, highlighting the presence of abiotic resources, together with the abiotic processes and biotic components of natural capital within the framework points explicitly to the need to use finite abiotic resources more sustainably and increase our research focus on the other two components.

Similarly, the framework makes clear that even for ecosystem services provided by natural ecosystems in urban areas, there is usually an input from human-derived capital, and this input must be considered in assessing the net benefit of those services. There are many ecosystems that are created for human benefit, such as cultivated land, urban forests, green roofs, urban parks, etc., which require resources for construction and long-term maintenance to be viable (Barot, Yé, Abbadie, Blouin, & Frascaria-Lacoste, 2017). For instance, while urban trees are recognized to provide important ecosystem services, particularly shade for thermal comfort, there are significant carbon emissions from maintenance activities of urban trees and from tree mortality (Strohbach, Arnold, & Haase, 2012). Even in the wet humid tropics, it is not possible to sustain green walls without regular irrigation. So, while evapotranspiration from green walls are known to produce cooling benefits and reduce energy consumption of cooled spaces in building interior, there are also energy costs associated with maintaining them that are seldom considered. A green wall that is sustained by consuming more water and energy than the cooling effect that it produces can hardly be considered to be providing net benefits. It is therefore essential to consider the life-cycle costs of systems such as green walls and bioretention systems, since in cities with a short real estate development the overall net benefits of green wall and green roof systems may never be achieved (Tan, 2017, 17). More generally, life-cycle analysis is important to determine how long a system must be in operation before it produces net positive benefits and can therefore be regarded as providing a UES.

The amount of human-derived capital into systems should thus be explicitly considered in providing UES. A proper accounting for extent of input versus benefits remains challenging and is an area where more research is needed (Beichler et al., 2017). We also highlight that although it is not possible for many artificially created ecosystems to be totally self-sustaining—green roofs, constructed wetlands, rain gardens, etc., require periodic maintenance for long-term functionality—a better understanding of life-cycle costs combined with design and innovation points to pathways to reduce the overall consumption of abiotic resources and human-derived capital. Useful references in planning UES are provided by large-scale ecological engineering systems which have been designed to function, as far as possible, like self-organizing natural systems (Barot et al., 2017). Expanding the focus on UES to also include urban services like housing, transportation and sanitation, etc. highlight their dependence on natural capital and make them explicit targets to adopt more resource-efficient solutions to deliver these services.

(3) *Enhance UES through technology*

As there is a limit to the extent to which natural ecosystems in urban boundaries can meet human needs, increasing UES can and should leverage advances in technology and innovations in design. Technology should be harnessed to deliver UES in association with the built or technological components of cities. The intersections between the natural, built and technological components of cities provide rich opportunities for the incorporation of novel methods and materials to improve performance of infrastructure systems while reducing both the consumption of resources and the generation of waste. For instance, there are many examples on integrated green-grey infrastructure systems for coastal protection (see Naylor, Kippen, Coombes, Horton, MacArthur, & Jackson, 2017). There is also an emerging array of building technology and materials that harness naturally occurring processes; these include materials that promote evaporative cooling by temporarily absorbing moisture (Wanphen & Nagano, 2009), photocatalytic coatings that remove pollutants deposited on building surfaces (Pinho, Rojas, & Mosquera, 2015), and phase change materials for thermal energy storage using latent heat for passive cooling of buildings (Akeiber et al., 2016). These examples illustrate the value of combining synthetic materials with abiotic processes and using them in built structures to produce benefits that are conventionally associated with the biotic component of natural capital, such as cooling effects produced by vegetation. Wherever the built component predominates, it should be the target of research aimed at minimizing resource consumption by improving efficiency and, if possible, making use of natural processes. This is not just a role to be fulfilled by engineers—the design profession including architecture and landscape architecture should pursue this role more actively through interdisciplinary collaborations.

3.3. Recommendations for further studies

We have thus far focused our attention on explaining the conceptual framework, the underpinnings for considering urban services as ecosystem services, and propositions which can be used with the framework to guide the provision of ecosystem services in urban areas. The value of a new framework, however, should be judged not only by its conceptual validity and adoption, but also by its practical value to promote more sustainable urban landscapes. In this regard, we highlight two areas of work which will require further studies. The first is how the framework intersects with related concepts, and the second is the limitations of the framework.

(1) Relationships with related concepts

Scholars have used different but cognate concepts to convey and operationalize the potential benefits humans derive from nature. These have been reviewed recently by Escobedo et al. (2018) and Pauleit, Zölch, Hansen, Randrup, and van den Bosch (2017), who highlighted overlapping connotations of “ecosystem services”, “green infrastructure”, “nature-based solution”, and “ecosystem-based adaptation”. Díaz et al. (2018) recently suggested using “nature’s contributions to people” to recognize more explicitly, the social sciences’ perspectives of human’s relationships with nature. Such a plurality in concepts could arise from differences in disciplinary origins of the terms, absence of shared perspectives among disciplines, and limitations in existing concepts to accommodate new perspectives that are continually developed by scholars. While it is necessary to delineate the relationships between these concepts, it would be counterproductive to define them too narrowly and so lose the flexibility of applying them under different contexts (Pauleit et al., 2017). This is especially true when planners are confronted with a multitude of concepts that need to be operationalized in land use planning. Mapping the interrelationships between concepts is a useful approach to delineate overlaps and complementary areas. For instance, Pauleit et al. (ibid) provided a useful mapping of the relationships between nature-based solutions, ecosystem-based adaption, green infrastructure and ecosystem services across the dimension of scope and existing state of operationalization of the concept in practice. Nesshöver et al. (2017) also compared nature-based solution with six different related concepts to evaluate overlapping meanings and clarify differences.

It is thus useful to examine how our expanded notion of UES relates to other concepts. For instance, how does green infrastructure fit in the conceptual framework (Fig. 3), which as we note in Fig. 1 is the next most published concept after UES? Notwithstanding that its meanings and usage have evolved with time, the most common definitions of green infrastructure refer to the spatial and physical network of green and blue spaces within and around urban areas (Ahern, Cilliers, & Niemelä, 2014; Albert & Von Haaren, 2017; Communication from the Commission to the European Parliament, the Council, 2013; Hansen & Pauleit, 2014; Tzoulas et al., 2007). We suggest that a broad interpretation of the term “green infrastructure” would include all those abiotic and biotic components of natural capital that are incorporated through urban planning and management into cities and their regions. However, when planning or regulatory agencies begin to describe green infrastructure as an *approach* to land use planning rather than as a physical network (see US EPA, n.d.), the concept to green infrastructure could conceivably refer to the process of planning and provision of “ecosystem services in urban areas” within the framework.

We also suggest that our framework embeds important paradigms in urban ecology, which has been recently described as progression in ecology *in* city, to ecology *of* city, and ecology *for* city (Childers et al., 2015). Ecology in city focuses on the analogs of natural ecosystems in cities, and we suggest that this broadly encompasses studies focused on understanding ecosystem services from natural capital in cities, i.e., “ecosystem services in urban areas”. Ecology of city takes a holistic view of cities as comprising not just the natural component, but also social, and built (or technological) components, and seeks to understand how complex interactions between these components define the characteristics of cities as complex systems. Ecology *for* city assumes a normative view combined with an action-oriented approach that studies ecology *in* and ecology *of* city should be used to advance societal goals of urban sustainability. Thus, “services of urban ecosystems” manifest the outcomes of studies in ecology *in* and ecology *of* city in proposing that both the natural and human-derived capital must always be considered in concert to deliver all the services required for human well-being. Ecology for city is the application of our framework guided by socially determined normative propositions. It thus seems possible to delineate the relationships between UES and these related concepts using our conceptual framework. As the literature on these areas is extensive, characterizing the interrelationships will require a substantial review that cannot be accomplished in this paper. Our intention here is to highlight another potential use of our framework and encourage more in-depth assessment to clarify and expound the interrelationships more clearly.

(2) Limitations of the framework

Our framework, as with the Daly’s Triangle (Fig. 4), appears to contain a paradox—if natural capital is indeed the basis for all urban services and human well-being depends on the provision of urban services, there should be increased exploitation of natural capital, including non-renewable abiotic resources, to increase human well-being. Such a broad framework thus needs to be accompanied by normative propositions. The three propositions we described are not exhaustive and further suggestions on these will need to be developed. In fact, we also feel that more will emerge as socially formed norms of human-nature relationships evolve over time, under the influence of social, economic, and cultural contexts of different societies. Such norms will have particular relevance to cultural ecosystem services, which are generally non-material in nature, but always context dependent as culture and landscapes have reciprocal relationships (Nassauer, 1995). In other words, in applying the framework, societies will develop propositions peculiar to their socio-cultural context.

A broad framework is useful in as much as it potentially encapsulates other concepts, but it lacks the detail needed to guide application, such as in policy formulation in areas of urban planning and design, and nature conservation in urban areas. The broad framing could also be challenging to operationalize in practice. For instance, in creating benefits for humans from nature, the framework implies that policy makers have to consider not just green and blue spaces, but also weigh the relative benefits between urban ecosystem services and urban services in terms of consumption of natural and human-derived capitals. This will require trade-offs between capital types and agencies in municipal authorities working outside their normal jurisdictional areas. In addition, the application of the framework by planners will need to consider local context, such as current planning laws and instruments, and other socio-economic considerations. The framework does not provide guidance on how such trade-offs, cross-agency negotiations or consensus-building could be managed, or how it can adapted to local conditions. It can, however, be used to set the overall context for applying techniques such as multi-criteria decision analysis in public sector governance.

Similarly, the framework by itself does not specifically highlight research gaps that should be addressed, as this is dependent on the lens that is used to read it. This is not unexpected, as the perception and application of ecosystem services is context-dependent (Felipe-Lucia et al., 2015). Therefore, an environmental economist may ask what are the relative values of natural versus human-derived capital in providing transport infrastructure; a social scientist may question to what extent do modern societies recognize nature's contribution to providing public transportation service;, an an urban planner could ask should a transport corridor cut through a conserved nature area to connect urban agglomerations. The application of the framework in different disciplines and contexts thus needs to be tested.

4. Conclusion

Urban ecosystem service has emerged as an influential concept guiding the development of urban landscapes towards greater sustainability and livability. As a concept however, it has been criticized for a lack of clarity on core definitions, for its anthropocentric focus, and its tendency to be over-broad, embracing everything that is beneficial from nature. In this perspective article, we focus on the dual meanings of "urban ecosystem" and its implications for our notions of "urban ecosystem services"—a narrow notion of ecosystem services from natural ecosystems in urban areas, and a broad notion of urban ecosystem services comprising the former group as well as all urban services that are prevalent in cities. Although these dual interpretations were mentioned in two early seminal papers on ecosystem services, there have been no clear proposals on how to apply them. Recently, Grimm and Cook (2015) suggested that these two meanings lead to an "ecosystem conundrum" and called for a broader framing of ecosystem services in cities. The conceptual framework presented here is an attempt to deepen that broader framing. We consider below the key contributions of this paper: (1) resolve the current ambiguity, (2) highlight the need to consider holistically avenues to increase UES, and (3) clarify relationships with related concepts.

Resolve the current ambiguity. The ecosystem conundrum ceases to be a conundrum when we separate an objective, ecological view of cities from the normative and socially desired path for cities to achieve urban sustainability. Using this perspective, all urban services, have their origins in natural capital, and as natural capital generates ecosystem services, by inference, urban services are in fact, urban ecosystem services. Such a broad definition of UES is potentially problematic if it is used to lend support to the continual exploitation of natural capital for human well-being and lead to worsening environmental conditions. Its use, therefore, has to be supported by normative positions developed collectively in human societies. We described three normative propositions on how the framework can be used. Importantly, by explicitly highlighting that urban services also draw upon natural capital, the need to use natural capital judiciously comes to the forefront, and society must be encouraged to seek methods to achieve this.

Highlight the need to view holistically multiple avenues to provide UES. Our literature review has shown that most UES studies have concentrated on the natural ecosystems, particularly on urban forest and green open spaces such as parks. We suggest that this is a restrictive view that omits the benefits derived from abiotic processes. Such processes include the energy and material flows generated by Earth's biogeochemical and biophysical processes. The examples presented in this article show how a stronger focus on these abiotic processes is needed, given the limitations of natural ecosystems within urban boundaries.

Provide a framework to clarify relationships with related concepts. The third contribution is that the framework is sufficiently broad to be linked to other related concepts on benefits that nature provides for humans. We used the concepts of Daly's triangle, and ecology *in, of,* and *for* city as foundations to underpin the framework, and illustrate how green infrastructure could be positioned within the framework. This is with the aim of facilitating their applications more precisely and fostering greater clarity of their use in future studies. We also suggested areas for testing in research and applied studies that could cut across disciplines.

Acknowledgements

We are grateful to the three anonymous reviewers for their constructive comments which have helped us to improve our manuscript. We also thank Mark McDonnell for the discussions which helped shape the manuscript. This study is part of the research project National Capital Assessment of Singapore, funded by the National Research Foundation, Prime Minister's Office, Singapore under its Campus for Research Excellence and Technological Enterprise (CREATE) Programme (NRF2016-ITC001-013).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.landurbplan.2020.103837.

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