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Scale and context dependence of ecosystem service providing units

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ABSTRACT

Ecosystem services (ES) have been broadly adopted as a conceptual framing for addressing human nature interactions and to illustrate the ways in which humans depend on ecosystems for sustained life and well-being. Additionally, ES are being increasingly included in urban planning and management as a way to create multi-functional landscapes able to meet the needs of expanding urban populations. However, while ES are generated and utilized within landscapes we still have limited understanding of the relationship between ES and spatial structure and dynamics. Here, we offer an expanded conceptualization of these relationships through the concept of service providing units (SPUs) as a way to plan and manage the structures and preconditions that are needed for, and in different ways influence, provisioning of ES. The SPU approach has two parts: the first deals with internal dimensions of the SPUs themselves, i.e. spatial and temporal scale and organizational level, and the second outlines how context and presence of external structures (e.g. built infrastructure or larger ecosystems) affect the performance of SPUs. In doing so, SPUs enable a more nuanced and comprehensive approach to managing and designing multi-functional landscapes and achieving multiple ES goals.

1. Introduction

Are we unwittingly eroding the landscapes we need to sustain life and well-being? How can we assess the indirect effects of landscape change on human livelihoods and quality of life? Ecosystem services (ES)[1] have been broadly adopted as a conceptual framing for addressing human nature connections (European Commission, 2011; UK National Ecosystem Assessment, 2011) and to illustrate the ways in which humans depend on ecosystems for the generation of goods and services that contribute to human well-being (Daily, 1997; Millennium Ecosystem Assessment, 2005). ES are generated and utilized within landscapes, and we still need to develop the understanding of the landscape – ES connection. In this article we offer an expanded conceptualization of these relationships through the concept of service providing units (SPUs)[2] as a way to assess and discuss the structures and preconditions that are needed for, and in different ways can help plan and manage for, provisioning of ES.

In 2005, Claire Kremen asked what we need to know about the ecology of ES, at that time focusing on the organisms performing functions that could translate into services. These she called "ES providers", acknowledging that these would be found at different ecological levels (e.g. species or communities) depending on the service in question (Kremen, 2005). Addressing similar issues, Luck and co-authors (2003) introduced the concept of SPUs in ecological research. Sharing much the same foundation as ES providers, SPUs emphasize the physical site for the interaction

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[1] ES is short for "ecosystem services".

[2] SPU is short for "service providing unit".

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that may eventually become a service in addition to organisms. Two main conceptualizations of SPUs have previously been used: as situated organisms and as physical places (e.g. Burkhard et al., 2009; Luck et al., 2003). We do not see these as mutually exclusive conceptualizations but rather as complementary perspectives; the SPUs can be, for example, individuals of a certain tree species, a specific land cover or use, or a specific site like a sacred grove, and they only exist actively when they provide ES to human beneficiaries. In this paper we use SPUs, defined by the smallest distinct physical unit that generates a particular ES and is addressable by planning and management, to explore the dimensions of ES generation within landscapes. We see landscapes of different scales as representations of multi-dimensional social–ecological systems (Berkes and Folke, 1998; Liu et al., 2007), made up by the different features of an area of land including landforms, water bodies, climate conditions, ecosystems and human elements such as land use, buildings and transportation structures, and interacted with by humans. All the factors shaping landscapes also potentially influence the generation of ES.

The ES research community is steadily accumulating knowledge about how internal qualities of SPUs such as species identity, structural diversity/biodiversity or habitat composition can affect ES provisioning (e.g. Maes et al., 2012). What is less well known is how spatial structures, configurations and dynamics at multiple scales may influence the output from specific SPUs, which are always situated in a specific landscape context. Spatially explicit information about ES is increasingly demanded from landscape and land-use managers and spatial/regional planners (e.g. Daily and Matson, 2008; Kienast et al., 2009). Landscape ecology, geography, architecture, planning and many other disciplines with explicit interest in spatial dynamics offer insights that could inform the future direction of ES studies, not least in heterogeneous mosaic landscapes such as cities (Gomez-Baggethun et al., 2013). Such insights come from studies on vulnerability (Turner et al., 2003), spill-over effects (e.g. Blitzer et al., 2012), complementarity (Colding, 2007; Dunning et al., 1992), trade-offs and synergies (Haase et al., 2012), sense of place and place making (Stedman, 2003), and size thresholds (Groffman et al., 2006).

This article will offer an expanded conceptualization of ES through their relationship to SPUs and in doing so present a more detailed approach for planners and managers to help them understand and integrate the context dependent nature of ES generation into the ES discourse and practice. We illustrate the usefulness of this approach by addressing SPUs in urban settings and how they can provide – under different circumstances – different ES. We then discuss how spatial properties may influence the landscape ability to deliver multiple ES and point to the most prominent gaps in current knowledge to suggest future research directions.

2. Internal dimensions and contextual factors

It seems provident to disentangle how and when internal and contextual factors matter to enable answers to questions not only of where ES are generated, but also under what conditions, of what quantity and quality, and for whom, as well as to advance our scientific understanding and help find practical ways of working with ES. We suggest a two-part approach for defining and describing SPUs. The first part deals with internal dimensions of the SPUs themselves, i.e. spatial and temporal scale and organizational level. The second draws on perspectives from fields of study such as landscape ecology, planning, geography, economic and vulnerability research to highlight how context and presence of external structures (e.g. built infrastructure or larger ecosystems) affect the performance of SPUs. Methods for addressing and analyzing these different dimensions are currently being developed (Burkhard et al., 2011; Frank et al., 2012; Koschke et al., 2012; Syrbe and Walz, 2012), and we do not review these efforts here, but instead focus on the conceptual advantages of combining internal dimensions of the SPUs and context dependences of SPUs into one comprehensive approach to ES analysis/assessment. Table 1 illustrates core components of this approach by describing the relationship between urban ES, the relevant SPUs and their scalar and contextual dimensions.

2.1. Internal dimensions of SPUs

2.1.1. Spatial scale

Although processes operating at different scales interact and influence each other (Gunderson and Holling, 2002), there is often one scale, level or range where a specific process or function can be best analyzed (Holling, 1992). ES emerge when a minimum scale threshold is met. The scale threshold relevant for the analysis of a given ES can vary widely, from large regions to small parcels of land or individual trees (Hein et al., 2006; Martín-López et al., 2009), and depends on the management or research question. Some ES may be adequately analyzed by focusing on a single spatial scale. For example, the nutrient contribution of vegetables grown in an allotment garden can be examined at the level of single plants, whereas amenity services provided by urban parks can be examined at the site level and processes of carbon sequestration by forests to regulate global climate can be analyzed at the global level. Addressing a single spatial scale may not always adequately capture some ES. Harvest of fish may be supplied at the levels of plot (e.g. pond), ecosystem (e.g. lake), continent (e.g. river) and biome (e.g. ocean), with more fish available for harvest as the spatial scale increases. Once the scale threshold is crossed the provision of an ES may increase in a linear or non-linear fashion with increasing size of the SPU, depending on the dynamics of the ES being assessed. Spatial scale can also change the SPU itself; aggregation of one type of SPU can eventually lead to the formation of other types of SPUs in the sense that the aggregation provides also other ES, or co-benefits. For example, urban street trees when considered as singular SPUs, may provide cooling and air pollution removal benefits, but when connected as elements in the larger urban forests, they can in addition serve as corridors between urban green patches and therefore contribute to a larger suite of ES. SPUs sometimes coincide with the service benefiting areas (Syrbe and Walz, 2012) but often they do not. For example, recreation and food provisioning associated with allotment gardening take place primarily within the garden site (Andersson et al., 2007) while carbon sequestration benefits are independent of where the sequestration takes place (Hein et al., 2006).

2.1.2. Temporal scale

The ability of SPUs to provide ES can vary over time. For example, enjoyment of nature has been shown to follow the flowering and breeding season while recreation related to beaches is more common during the summer (Martín-López et al., 2009). Some regulating ecosystem services, such as carbon sequestration and air purification, are markedly reduced during winter months when most deciduous trees have dropped their leaves (Black et al., 2000). Other ES, and thus their SPUs, are activated only during specific events. For example, an urban wetland SPU functions as a provider of flood mitigation services only during major rain events (Kubal et al., 2009) and cooling effects by urban vegetation become most important during heat waves (Depietri et al., 2011). Similarly, Koch et al. (2009) demonstrate multiple time scales at which coastal protection is influenced by natural processes including hours of the day, seasonal, decadal as well as occurrences of extreme events. For example, coastal protection is generally highest when the tide is low but there are multiple non-linear processes and relationships in place that may

Table 1
Urban ecosystem services and their service providing units (SPUs) organized by type (provisioning, regulating, supporting, or cultural), SPU, spatial scale, temporal scale, level of organization, and context dependency. SPUs refer to single or multiple types of SPUs that can, depending on spatial and temporal scale and context, provide the different ecosystem services. Spatial scale describes the relevant scale (local, regional, or scalable across local and region) at which services are produced. Temporal scale describes the timing of ecosystem service production, which can be constant, seasonal, related to individual or even unique events, or driven by mobile SPU components. Organizational level refers to the baseline ecological level at which services are first produced, including by individuals, populations, as part of ecological communities or ecosystems. Context dependency describes the ecological, social–technical, cultural, and problem context affecting SPUs. Ecological context refers to the influence of surrounding ecological structures and dynamics that affect SPUs (e.g. presence of floral resources for pollinators); social–technical context refers the requirement of mediating social factors (e.g. legal access) or technological infrastructure and equipment (e.g. infrastructure to capture and deliver drinking water) necessary for services provided by SPUs to be utilized; cultural context refers to those SPUs that are only utilized when occurring within a particular cultural context that values or receives the ecosystem services benefit; and problem context refers to SPUs that only exist in the event of a particular environmental problem (e.g. flood mitigation is only provided in the event of a flood).

Ecosystem service	SPU	Spatial scale	temporal scale	Organizational level	Context dependency
Provisioning					
Food: produce and crops	Crop fields, fruit trees, gardens	Local, scalable	Seasonal	Individual or population	Social–technological, ecological
Food: livestock	Livestock + pasture	Local, scalable	Seasonal, in some cases mobile	Individual	Social–technological
Food: seafood	Fishing site + fish stocks	Local, scalable	Mobile, seasonal	Individual or population	Ecological, social–technological
Drinking water distribution	Watershed	Local, scalable	Constant or seasonal	Ecosystem	Social–technological
Wood and fiber	Trees, shrubs	Local, scalable	Constant or seasonal	Individual	Social–technological
Regulating					
Erosion control	Trees, shrubs, herbs	Local	Event, constant	Individual or population	Problem
Flood control	Wetlands	Local, regional	Event	Ecosystem	Ecological, problem
Storm water runoff mitigation	Trees, shrubs, permeable surfaces	Local	Event	Population	Ecological, problem, social–technological
Water quality enhancement (N, P, coliform, Total suspended solids)	Wetlands, vegetated surfaces	Local, regional	Constant	Individual or ecosystem (different processes)	Ecological, social–technological, problem
Air purification/air quality regulation	Forests, trees, shrubs	Local, regional	Constant or seasonal	Individual	Problem
C sequestration	Plants, soil bacteria	Regional	Constant or seasonal	Individual	
C storage	Plants	Local, scalable	Constant or seasonal	Individual	
Pest control	Interface between crop field and predator habitat + predators	Local, regional	Mobile, seasonal, event	Population or ecosystem	Ecological, problem
Temperature regulation	Trees, shrubs, herbs, lawns, wetlands and water bodies	Local, regional	Seasonal, event	Individual	Problem
Noise reduction	Trees, shrubs, vegetated surfaces	Local	Constant, event	Population	Social–technological, problem
Supporting					
Pollination and seed dispersal	Pollinator + plant/crop	Local	Mobile, seasonal	Individual or population	Ecological
Cultural					
Esthetic value	Trees, parks, landscape vistas, flowering plants, birds, gardens, etc.	Local	Mobile, constant, seasonal, event	Individual, population, community, ecosystem	Ecological, social–technological, cultural
Recreation and cognitive development	Parks, nature reserves, gardens, lakes and waterways, etc.	Local	Mobile, seasonal, constant	Individual, population, community, ecosystem	Ecological, social–technological, cultural
Educational opportunities	Nature reserves, open farms and gardens, visitor centers, green areas, etc.	Local	Constant, mobile, seasonal, event	Individual, population, community, ecosystem	Ecological, social–technological, cultural
Animal sighting	Parks, nature reserves, gardens, lakes and waterways, trees, etc.	Local	Mobile, seasonal	Individual, population, community	Ecological, social–technological

affect the level of protection such as geomorphology, submarine habitats, wave regime or tidal range (Liquete et al., 2013). Species movements beyond the spatial limits of the SPU has temporal implications as organisms critically important for the delivery of a certain ES may be temporarily absent, which renders the SPU inert.

2.1.3. Level of organization

At local scales, the level of ecological organization is important for identifying the SPUs. The level of organization of SPUs may vary from the individual level to the population, species, community or ecosystem (Kremen 2005). The level of organization is connected to – but not interchangeable with – spatial scale, but we suggest that a particular ES emerges at a specific level or threshold of organization defined by interactions between organisms. Thus the individual plant may provide habitat for insects but not for large mammals. The latter require a large number of individual plants and more complex plant communities in the form of a forest ecosystem (a higher level of organization than the individual plant). For example, pollinators need a stable supply of e.g. nectar sources and nesting sites over multiple seasons (cf. Lonsdorf et al., 2009), which do not occur at the species or population level but can emerge at the community or ecosystem level. Pollination thus needs a minimum level of ecological complexity as a condition for the ES to occur. On the other hand, shading from trees can emerge at lower levels of organization such as individuals or populations.

2.2. Contextual factors affecting the SPUs

Since ES flow from ecosystems to people, and ecosystems themselves are shaped by both social and ecological processes, there are often mediating factors that affect the translation of an ecological function into a service. Here we refer to mediating factors as elements and system components that do not provide ES themselves but help realize services in the prospective SPU. We group these mediating contextual factors as social-technological, dependent on particular environmental problems, ecological or cultural.

2.2.1. Social–technological context

The use and benefits of SPUs and their potential ES may require mediating and complementary factors such as labor, technology and institutions to access the services and thus actually derive benefit (Syrbe and Walz, 2012). For example, institutional issues of access, user rights, and socioeconomic factors such as age and income can mediate whether a particular individual or community is able to realize ES benefits (e.g. McPhearson et al., 2013), even when the ES is generated in an SPU. Similarly, technological mediation is often critical to realize ES, since various kinds of technology provide the infrastructure necessary to access the ES. Technological infrastructure can include hi-tech transportation and built infrastructures such as roads, rails, boats, and artificial beaches, but also low-tech elements such as docks, jetties, benches, and footpaths. These kinds of mediating elements support the delivery of ES by providing necessary infrastructure and tools for accessing SPUs or ES directly, including a large array of ES such as agricultural products, seafood, drinking water and recreation (Table 1).

2.2.2. Environmental problem context

Some SPUs mitigate environmental problems and are only relevant in the presence of the problem. These SPUs may for example provide water and air purification, flood mitigation or noise reduction. However, without the problem itself the service does not exist. Air purification is most important in severely polluted cities and protection from natural hazards such as flooding and storm surges is closely linked to certain climatic regions and specific sites. SPUs that may mitigate such hazards are active only during the hazard and are otherwise latent. As these SPUs often act as barriers between the problem and the beneficiaries (Fisher et al., 2008) they often have benefitting areas outside the actual SPUs. Thus, in order to understand and assess the relative contribution of a potential SPU it is important to know the source, timing, and nature of the environmental problem being mitigated by an ES, and the location of the expected benefiting area. This can of course be difficult, but the more information and understanding we have the better we should be able to manage and plan to meet ES goals. For example, the various sources of social and demographic information such as social media and census data (e.g. Wood et al., 2013) could provide information for understanding vulnerability and therefore better identify the problem context.

2.2.3. Ecological context

Many ES are generated in the context of a landscape much larger than the SPU itself, such that without the SPU, the landscape is unable to deliver the service. At the same time, the service delivered from the SPU is influenced by the landscape. SPUs can be either completely fixed in space (e.g. plants, ecosystems, land covers) or partially dependent on a mobile component (e.g. animals). The behavior and community dynamics of mobile organisms are often influenced by the spatial distribution of resources at larger scales. For example, fruit production in an orchard depends on the presence of pollinators, but the pollinators themselves are influenced by factors outside the orchard such as additional habitat resources, potential for meta-population dynamics, and additional nectar sources. Although these organisms provide ES locally, a specific individual can engender ES in several different locations (Kremen et al., 2007; Lundberg and Moberg, 2003), in essence making the SPU mobile.

The actual delivery of ES by mobile organisms places demands on landscapes in terms of the connectivity of the larger green infrastructure as well as local habitat quality and therefore the quality of ES generation. Stepping stones and corridors that connect SPUs are important to the delivery of ES (Murphy and Lovett-Doust, 2004) and should be an important consideration in planning and management for ES. For example recreation provided by bird watching in urban contexts may depend on bird diversity, which may be determined by not only the size or ecological quality of the birding site (the SPU in this case), but also on the connectivity to other sites and the larger region.

2.2.4. Cultural context

The ES humans derive from SPUs depend on human perceptions, values, and social norms (Breuste et al., 2013), which may be influenced by cultural background, religion, sense of place and community (Andersson et al., 2007; Milligan, 1998). For example, different cultures have disparities in their preferences for various recreational environments and in the kind of recreation that may take place in an SPU (e.g. Kabisch and Haase, 2014). Similar symbolic and spiritual values can have different SPUs across cultures and religions (e.g. Berkes, 1999). For example, different cultures may have different perceptions of what constitutes meaningful cultural heritage in a landscape (cf. Stephenson, 2008), or the appropriateness of different land parcels as burial sites (e.g. sacred forests or cemeteries). Furthermore, what some people may perceive as a source of ES others may perceive as a source of disservices. For example, green quiet areas in cities can be for many a source of opportunity for recreation and relaxation (Chiesura, 2004) while others may perceive them as unsafe, dangerous places (Bixler and Floyd, 1997).

3. Application

To illustrate how our more contextual approach for analyzing and assessing SPUs can be used we developed an extensive summary table (Table 1) detailing the case of urban ecosystem services and their associated SPUs. In the following we first explain the reasoning behind the table and then use the example of urban trees and site specific studies to illustrate how their role as SPUs depend on scale and context.

3.1. Urban ES and their SPUs

An extensive list of urban ES based on the current literature (Gomez-Baggethun et al., 2013) was used as the basis for Table 1. For each service we listed at least some of the relevant SPUs – depending on the city, climate, biome and so forth SPUs will vary globally. The emphasis of the table is primarily on the scalar dimensions; it is difficult to be specific about the contextual factors when addressing ES broadly, so listings in the table should be read as the primary domains in which to look for contextual factors. Spatial scale indicates at what size a unit becomes an SPU, i.e. when it starts to deliver a service. Once this threshold has been crossed many services are scalable in the sense that a larger SPU contributes with proportionally more of the service, for example a large area of crop land can provide more food production than a small lot, all other things held equal. At the temporal scale Table 1 distinguishes between constant supply and different frequencies of temporal variation, for example as a result of a dependence on a mobile component that may or may not be present at any given time. All ES need a baseline ecosystem support, but beyond that we use the level of organization to indicate the level of ecological complexity minimally required to deliver the service, i.e. how many individuals or species are involved in the generation of the service.

3.2. Urban trees as SPUs

Urban trees contribute to ES and form SPUs at multiple spatial scales. The smallest SPU is the individual tree (it can for example provide shade or fruit). Many of the ES trees provide are scalable, meaning that it is relatively easy to aggregate the added value of more trees (e.g. carbon storage and sequestration), while other ES will not be realized until the number of aggregated trees crosses a threshold. For example, lines of street trees may serve as corridors connecting larger green patches. In this case, trees that otherwise may be considered individually located, create an SPU (the corridor) that adds a habitat support function, often considered a supporting ES, and trees aggregated to the level of forests may provide habitat (Fig. 1).

Some services offered by trees are only available at specific times. Cherry blossoms, for example, will only last for a few weeks each season but are much appreciated in Japan for their aesthetical qualities and their transience (Keene, 1995). Fruit trees have their specific harvest times and deciduous trees will exhibit distinct seasonality in some of the services they provide (e.g. noise reduction and carbon sequestration).

Other ES provided by trees depend on the social–ecological context in which the trees are located. Food production by trees, for example, syrup produced by Sugar Maple trees in the U.S., Canada, and elsewhere, depends on the technical extraction of maple syrup from the tree, processing, packaging, and delivery in order to realize the ES potential of trees (Fig. 2). The social context is similarly important to ES provisioning by trees. For example, a group of trees may provide services of recreation and education if located and maintained within a park, but they depend on the park to attract people. If no residents visit the park, then there is no recreation service. The same grouping of trees may also provide ecosystem disservices such as providing shelter for illicit activities,

Fig. 2. Tapping Sugar Maple (*Acer saccharum*) trees at Pound Ridge, New York, USA. Maple sugar tapping represents a seasonally occurring food production ecosystem service, which has long standing cultural traditions in many northern countries. In this picture we show the socio-technical context required for Sugar Maples to function as SPUs (Photo credit: Timon McPhearson).

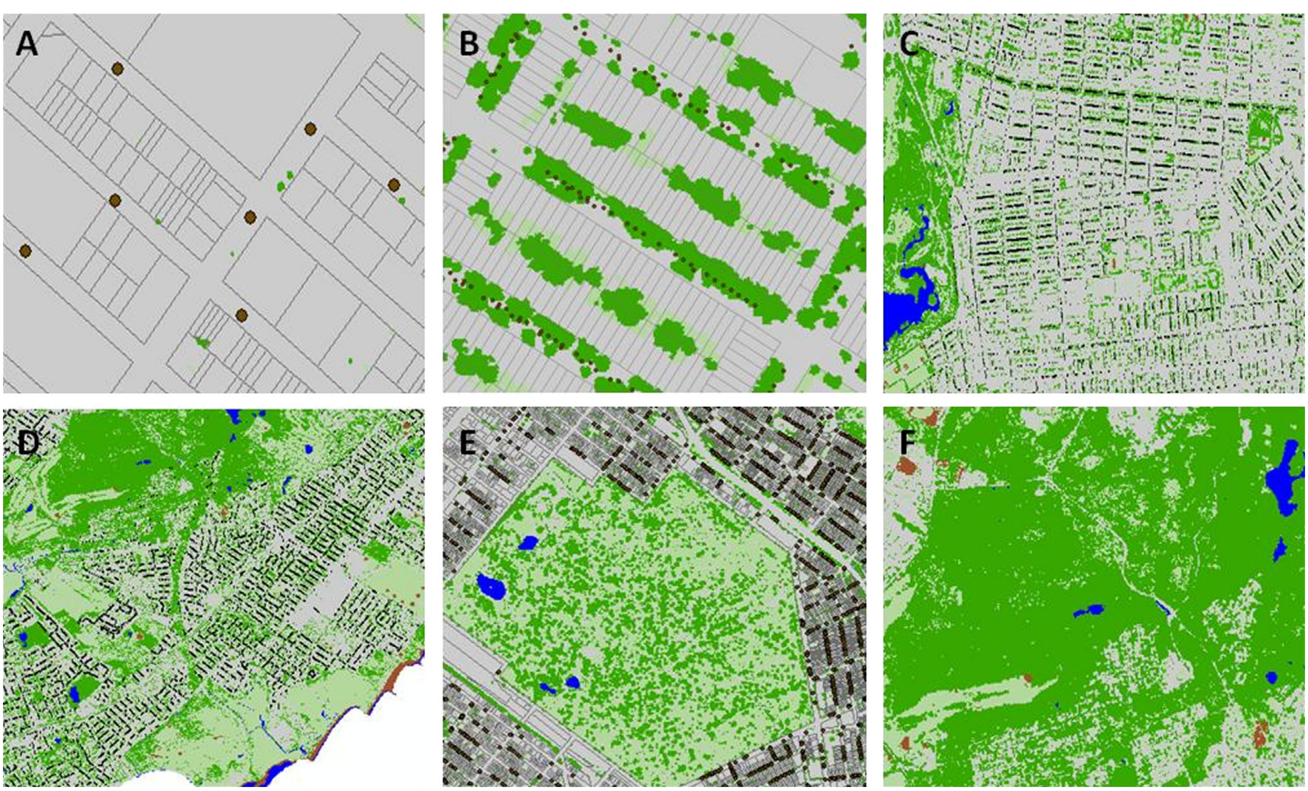

Fig. 1. Urban tree SPU configurations: (A) individual scattered street trees; (B) dense street trees; (C) street trees as corridors connecting small and medium size urban green patches; (D) dense street trees corridor connecting large urban parks; (E) disconnected urban green space with scattered trees (in this case a cemetery); and (F) large urban forest.

if located in a deserted urban vacant lot instead of a park, emphasizing the importance of social and technical context of SPUs to ES provisioning (Lyytimäki and Sipilä, 2009).

Air pollution removal depends on the presence of air pollution, here discussed as an environmental problem context, and thus varies by the environmental, social and technical factors that produce air pollution in cities such as wind patterns, traffic density and land uses (Jim and Chen, 2008; Nowak et al., 2006). As a result, trees in high-traffic streets or industrial zones provide higher ES value than those in small residential streets (ibid). The amount of cooling that is achieved and its impact on reduction in energy use highly depends on the co-location of a street tree and various urban structures including nearby buildings such that shading by trees decreases the heat load to buildings, and thus decreases energy use for cooling (Rosenzweig et al., 2009). Also energy savings are potentially very high in areas that are subject to high temperatures while they may be negligible in cold cities.

Especially when connected to a larger green structure individual trees can offer opportunities for wildlife spotting (cf. Tyrväinen et al., 2005), or help sustaining tree dispersal and regeneration (Lundberg et al., 2008) and thus long term presence. This is particularly true of more complex SPUs where the ES depend not only on the trees themselves but also on interactions with mobile components such as pollen or insects.

As the often most obvious component of urban green infrastructure, trees are recognized and related to by people. However, the value attached to trees differs with the cultural context. There is a rich literature on sacred trees and how trees may add to sense of place and community cohesion, but there are also contrasting examples (e.g. Kronenberg, 2015) where the cultural setting means trees can have primarily negative connotations.

4. Discussion

Researchers and practitioners have a growing understanding of many of the basic units that can eventually provide different ES (e.g. Daily et al., 2009). However, this knowledge, in itself, is often inadequately detailed and does not always consider trade-offs and synergies among multiple ES. When applying a comprehensive SPU approach, the usability of this knowledge may increase. For example, once the basic components of urban green infrastructure that can serve as SPUs for different ES are known, scale considerations will help determine when they actually form an SPU, and what happens beyond this threshold. With the SPUs defined, this approach can then assist with addressing how important contextual factors outside the SPU can promote or suppress the magnitude of the delivered ES. Because scale and context are both critical factors within the ambit of landscape planning and design, we suggest that this approach is important to operationalizing ES in policy, planning, management, and urban design.

The context and scale considerations within our approach for analyzing and understanding SPUs indicate specific ways in which social, technical, and ecological infrastructures all influence the generation of ES in SPUs, as does the existence, sometimes temporary, of particular environmental problems that some ES address. In order to utilize services provided by different landscapes, managers, planners, and designers need to know where the ES come from and how they relate to other ecological and built components within the systems. This requires explicitly dealing with the complicated and complex nature of social–ecological systems. It also requires moving beyond managing or planning for individual, isolated built or green infrastructures to meet ES goals, to more systematic approaches that take into account relationships between SPUs, their context dependent nature, and incorporation of scalability.

The complexity of landscape dynamics also means that seemingly unrelated changes in the urban landscape can have consequences for the generation of a diverse set of ES. Although we primarily use urban systems to exemplify and illustrate the SPU approach, its application is not limited to urban systems. The SPU approach can be utilized from a number of different entry points, e.g. starting with specific services and assessing a particular location or type of land use, or starting with a resource as in the example of urban trees. The approach demonstrates that ES must be addressed across spatial and temporal scales, and that ES are not independently delivered by ecosystems to humans but are co-produced by humans and ecosystems within interacting social-ecological and technical contexts.

Multi-functionality and bundles of ES related to different land uses have been previously explored (De Groot et al., 2010; Foley et al., 2005; Raudsepp-Hearne et al., 2010) and to some extent related to internal characteristics of these land uses, but we argue that using an SPU approach can further this understanding. If we understand the actual SPUs as defined by ES themselves and not by the associated land use or some other proxy, we will be better able to understand how and when different SPUs might be combined, organized, and planned to ensure a sustained supply of bundles of critical services. When the different SPUs are known they can be analyzed as parts of different land uses and thus help explain the roots of multi-functionality, or at the very least, the environmental aspect of multi-functionality. With the added understanding of scale and context dependence of ES provisioning, we can advance our understanding of when bundles of ES unravel as a consequence of reducing the size of an area (as there might be thresholds) or the wider implications of land use change (e.g. loss of local biodiversity due to regional fragmentation of green infrastructure).

This SPU approach for assessment and analysis helps make clear which SPUs are essential as building blocks for designing multi-functional green infrastructure, and which and when green infrastructure components may and may not be partially substitutable (as most ES have multiple SPUs). From the examples above and Table 1, we suggest that different components of green infrastructure (e.g. urban parks) generate multiple ES, either because specific SPUs can provide several services or because these kinds of green areas are made up by several SPUs. This multi-functionality is crucial to meet the goals and demands of a diverse group of ES users (Mander et al., 2007). Additionally, since the generation of ES is context dependent, there are multiple points of entry for influencing ES in urban planning, management, and design. Modifying an SPU may help achieve a particular ES goal, as can the manipulation of the specific context an SPU is set within. Efforts to achieve particular ecosystem services goals, whether for regulating, provisioning, supporting, or cultural services, will require taking into account and intentionally manipulating both the SPU itself, quality and size, as well as the context it exists within.

5. Conclusion and future research needs

Understanding SPUs as context dependent, spatially explicit units for the generation of ES is critical for ES assessment, analysis and valuation because it enforces the inclusion of the components, conditions and contexts that make ES production possible. The novel approach presented in this article combines earlier work on SPUs and explicitly considers internal dimensions as well as social–ecological contextual factors. Using this approach it becomes clear how different spatial arrangements, within different social–ecological contexts can influence ES generation in different landscapes. In doing so, it enables a more nuanced approach to managing and designing multi-functional landscapes and achieving multiple ES goals, which is particularly critical for planning, management and policy making in complex and heterogeneous settings like cities.

Whereas the focus of this paper is on the supply side of ES, the SPU approach can be extended to also include demand for ES and can be used to assess the spatial mismatches between supply and demand. In this manner, demand can also be understood as a contextual factor or be conceptualized as service benefiting units.

To operationalize the SPU approach further research is needed on the typology of SPUs and their relationship with ES and contextual factors. A better understanding of thresholds (in scale and for contextual factors) relevant to the production of different ES, the ways change in SPUs impact bundles of ES, and the ways SPUs combine to create multi-functional landscapes will help develop the SPU approach and enable the inclusion plex dimensions of ES production in planning and decision making.

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