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Ecosystem Function

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Definitions

Ecosystem functions are hierarchical bundles of ecological processes that sustain the internal organization and structure of ecosystems in space and time. These ecosystem functions are the fundamental set of interlinked energy/material/information exchange processes performed by the ecosystem. They can be understood as hierarchical aggregations of several processes unfolding in a specific direction or arrangement. Ecosystem functions are possible to identify by particular outcomes they produce. For instance, carbon stocks are a primary outcome of the function of carbon sequestration, which aggregates a multifaceted set of processes: primary production, respiration, decomposition, burial in sediment, and loss in various forms to atmosphere or streams.

The Use of the Ecosystem Functions Concept in Natural Sciences

The term ecosystem functions has been broadly used in ecology, landscape and urban ecology, and related disciplines. Forman and Godron's (1986: 593) define function – without explicit application to an ecosystem, rather to a landscape and a corridor – as "the flow of mineral nutrients, water, energy or species." Forman and Godron's function definition is placed within his overall approach to landscape functioning, where he relates landscape structure with flows of energy, water, minerals, animals, and plants: "Determining and predicting these flows or interactions among landscape elements is understanding landscape function" (Forman and Godron 1986). Forman's "functioning" approach to understand how ecosystems work has been broadly applied in natural sciences. In systems ecology, understanding structure and function is essential for assessing ecosystem resilience, that is, determining the capacity of ecosystems to sustain their internal processes after disturbances: "functions are flows and changes of state as energy passes through network structure" (Odum 1994: 19). An ecosystem's resilience depends on the maintenance of certain ecosystem functions.

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In ecology and related disciplines like landscape and urban ecology, the term function has been traditionally associated to the role played by a particular ecosystem component, like plants or microorganisms. Alberti (2016: 226) defines ecosystem function as “the flux of energy, organic matter, or nutrients in an ecosystem, including the flux of biomass associated with trophic interactions. Function is expressed as a rate of change of an ecosystem property.” This definition is based on the fundamental role of biodiversity for ecosystem resilience, where different species perform specific functions, determining the efficiency with which resources are processed within an ecosystem (Alberti 2005). The term has also been understood as the particular way in which ecological processes interact with specific material ecosystem components and compartments, like soil, water, or air. The word “functioning” is sometimes used in these contexts to avoid any implication of intentionality, purpose, or teleology on the part of organisms and ecosystems.

The term function has been widely applied in the domain of ecological modeling, where a particular subset of processes is mathematically understood by establishing a quantitative relationship between one ecosystem output (dependent variable) as a “function” of – i.e. depending on and/or being explained by – the subset processes, the actual transformations, or movements of energy/material/information as independent variables in conjunction with influencing factors. Here ecosystem functions are quantitatively narrowing the processes relationships, sometimes requiring highly hierarchical models.

From Processes to Functions and Services

It is possible to distinguish two main dimensions of the ecosystem functions concept: (1) the role played within ecosystem functioning, addressing the relevance within the overall ecosystem performance in terms of ecological integrity and (2) the relevance within the human sphere, concerned with the role played in human-environment interactions.

The first approach broadly used in ecology has traditionally understood ecosystem functions as bundles of ecosystem processes that can be linked as operating within a particular ecological system (Loreau et al. 2002; Hector et al. 2007), regardless their relevance for humans and society (Gómez-Baggethun et al. 2010). Here ecosystem functions are understood in a strict ecological sense, focusing on how they configure and sustain ecological integrity. In a broader ecological sense, understanding ecosystem functions as bundles of complex ecological processes is a powerful analytical distinction, supporting the measurement and management of ecosystems, considering that ecosystem structure and function are mutually dependent, making functions, structure, and organization entangled phenomena within ecosystems (Odum 1994). This approach to functioning remains broadly useful in ecology (Balvanera et al. 2005; Cardinale et al. 2011) supporting the understanding of ecosystem complexity. Such knowledge is crucial for maintaining ecosystem resilience and integrity, which are in turn required to meet the aims of sustainable management in pursuit of the SDG.

Since the 1960s, and even more in the last 20 years, scholars have addressed how the functions of nature served humans and society, therefore systematically connecting human well-being to ecosystem functions (Odum and Odum 1972; Helliwell 1969; de Groot 1992; de Groot et al. 2010). Understanding ecosystem functions as links between ecological processes and human well-being is a practical approach. It recognizes that the function represents the ecosystem’s potential to deliver a particular service(s) based on ecological structure and processes (de Groot et al. 2010). Here ecosystem functions can be defined as a particular action, work, or role performed by an ecosystem as an aggregate or bundle of ecological processes delivering specific benefits (Bennett et al. 2009; Spake et al. 2017; Liu et al. 2019). To distinguish a specific ecosystem function as an overall result of complex ecological processes, it is necessary to identify the functional role within the system, the human relevance of the particular action, and what socially impactful outcomes can be associated with it.

Linking functions to human well-being has been the basis for the development of the ecosystem services concept. Such human-facing application of the EF concept has been stimulated by the spread of the ecosystem services approach to several scientific disciplines with increasing applications in decision-making (Hansen et al. 2015; Cortinovis and Geneletti 2018). In the context of human perceptions, ecological processes, functions, and services are all basically assessed by the manner in which they serve society. De Groot (1992) identified environmental functions as the capacity of an ecosystem to sustain human activities and well-being. On this basis, he proposed a framework for integrated assessment and valuation of ecosystem functions, goods, and services, in which regulation, habitat, production, and information were identified as the four fundamental functions that emerge from the ecosystems' structure and processes (de Groot 1992). This strategy translates the vast diversity of ecological structures and processes in a reduced number of manageable ecosystem functions. This smaller suite of functions can be modeled to determine the capacity of an ecosystem to provide services (de Groot et al. 2002). Such a human-focused approach charted a conceptual path for linking functions to services. This path has been followed by several authors and sustains The Economics of Ecosystems and Biodiversity (TEEB) and the Common International Classification of Ecosystem Services (CICES) frameworks (de Groot et al. 2010; Haines-Young and Potschin 2018). The TEEB report (2012) made ecosystem functions a central concept in understanding the benefits society obtains from specific biophysical structures and processes. While directly linking ecosystem functions to human well-being, TEEB recognized that: "no fundamental categories or completely unambiguous definitions exist for such complex systems" (de Groot et al. 2012: 10). For CICES, ecosystem functions are "the subset of the interactions between biophysical structures, biodiversity and ecosystem processes that underpin the capacity of an ecosystem to provide ecosystem services" (Potschin and Haines-young 2016: 3). This has been the basis for the cascade model, where the EF definition is used to emphasize specific characteristics, i.e., processes that interact to make a service benefitting humans. EF are, in this approach, taken to be the "subset" of characteristics or behaviors possessed by an ecosystem that determines or "underpins" its usefulness for people. This approach recognizes the ambiguity of the term "functions" which is also used to mean "processes" or "purposes" (Haines-Young and Potschin 2017). Rather than resolving the ambiguity, the cascade framework concentrates on the identification and systematic classification of ecosystem services for its application in planning and management. However, there is an explicit recognition that "the sustainable management of land and ecosystem services will probably require further work on characterising ecological functions" (Potschin and Haines-young 2016: 3).

Still in several disciplinary and institutional contexts, such as forestry, central European landscape ecology, and spatial planning, the term function has been applied in both ways, assigning roles to processes within human activities and in ecosystem performance (Bastian and Steinhardt 2002). In forestry for instance, applying the lens of human activities to forest, identifies such functions as recreation, wood (biomass) production, as well as biodiversity. Indeed, the term "function" has been used in the scientific literature interchangeably with process, and even with services, with ambiguous results (Jax 2005; La Notte et al. 2017). However, there is increasing acceptance of the usefulness of the analytical distinction between ecosystem functions and services, keeping the concept of function in its ecological meaning of how ecosystems perform a particular subset of complex processes to sustain its internal organization and structure and therefore providing services to society.

Ecosystem Functions, Structure, and Organization

It is possible to understand ecosystems in terms of flows of energy, following thermodynamic principles (Odum 1994). Flows of energy build ecosystem structure and generate order (organization). Based on this order, ecosystems maintain themselves and transform materials through a set of fundamental, complex, and interlinked processes that are at work sustaining ecological integrity. These processes allow ecosystems to perpetuate their internal structure and organization.

Ecosystems' components are structured and organized in a multidimensional manner with manifold interrelated processes and feedbacks. For instance, mineralization and humification of organic litter include many processes working together that, on the one hand, deliver plant-available nutrients and, on the other hand, that build up new organic matter and substance that increase the nutrient and water storage within the soil. Thus, the EFs mineralization and humification integrate a variety of subordinate processes. Ecosystem science and biogeochemistry have made great progress in discovering the mechanisms and interaction of these subordinate processes (Weathers et al. 2016). EF can be qualitatively and quantitatively described by choosing meaningful biophysical indicators. The specific indicators selected depend on the level of hierarchical detail chosen, the desired level of detail, the spatial scale of interest, or the jurisdiction(s) or needed for application in which EFs are of interest (Pickett and Cadenasso 2002).

Ecosystem Functions and Management

Understanding EF as major combinations of processes helps structure the understanding of ecosystem complexity, providing insight into alternative ways to manage ecological integrity. The analysis, assessment, and measurement of EF have been largely applied in scientific disciplines such as ecology, systems ecology, landscape and urban ecology to characterize ecosystems. The modeling of EF is a fundamental tool to assess the sustainability of ecosystem management (Chapin et al. 2011; Rieb et al. 2017).

Ecosystem functions are influenced by their location in landscape mosaics (Forman and Godron 1986; Cadenasso et al. 2006a). Sustainable development calls for human actions, many of which are linked to the landscape scale, on which spatial ecological units can be delineated. Those units are called ecotopes and understood as the material expressions of the theoretical concept of ecosystems. The fact that neighboring ecotopes influence each other to differing degrees is fundamental for achieving sustainable management. Especially in hilly terrain, or when groundwater flow or inundation is present, there is connectivity between the spatial units that, at first sight, seem to be discrete units. Forest patches, pastures, lakes, and residential are highly integrated vertically and horizontally within the ecosystem. All ecotopes are horizontally coupled by flows of matter, energy, and information. Under this landscape perspective, the functions that neighboring adjacent ecosystems (ecotopes, etc.) perform can be assessed and modeled (Rose et al. 2017). Examples can be the habitat function of a forest patch and forest field ecotone for biological pest control. In many cases, people benefit from these biophysical functions amalgamating the two aforementioned dimensions of ecosystem functions.

The distribution, abundance, and dynamic interactions of species can be a good indicator of an ecosystems' condition and are therefore relevant for ecosystem management. Often the disappearance of species precedes changes in ecosystem functions and overall resilience (Rapport 1992). There are a variety of possible target species and measures of ecosystem function (i.e., energy flow, nutrient cycles, productivity, species interactions). Several scholars suggest that net primary production (NPP) is an excellent summarizing indicator, which is a result of, and determines the changes in several ecosystem functions (Alberti 2005; Costanza et al. 2007). However, the selection of adequate EF indicators depends on what is aimed to know or to preserve or restore.

Ecosystem Functions Versus Landscape Functions

Landscape function has been defined as "the capacity of a landscape to provide goods and services to society" (Willemen et al. 2008: 34), including all types of material goods such as crops or timber and services as landscape aesthetics and water regulation (de Groot 1992; Wiggering et al. 2006). This expression has been largely used in land systems science and also in landscape planning, especially in Germany where the concept has been legally defined (Syrbe et al. 2007).

Landscapes can consist of mosaics of different ecosystems, in which neighboring ecosystems are linked to each other by flows of matter, energy, and information. The functioning of these spatial ecosystem complexes is studied by landscape ecology. In this sense, uni- or bidirectional transfers of, e.g., water, nutrients, or sediments can be understood as ecosystem functions, which are in line with the clear distinction between ecosystem functions and ecosystem services. For some functions, such as provision of food and other resources, the distinction is simply a matter of scale, of others, especially some regulating services (effect of landscape configuration on regulating water flows in a watershed, or aesthetic qualities of the landscape); the function has a different "quality" at the landscape scale compared to the ecosystem scale. Therefore, landscape functions and ecosystem functions cannot simply be treated as synonymous.

Landscape function is an emergent property of the mosaic of specific ecosystems (ecotopes) within it. The spatially explicit configuration of ecotopes, the nature of the ecotope or ecosystem boundaries, and the neighbor-to-neighbor flows of energy, material, and information, as well as long-distance flows within the mosaic, all contribute to the emergent landscape function. Furthermore, if landscapes are characterized by having relatively coarse scales, that is, involving large distances within them, very likely most landscapes will include human actions and artifacts (e.g., Forman and Godron 1986), lending an additional source of complexity to their function beyond that of the constituent ecosystems.

Urban Ecosystem Functions

Urban areas form highly spatially structured mosaics of built habitats, planted and managed habitats, relic and emergent "natural" areas, and habits that are hybrids of constructed and biophysical elements. The spatial constituents of the urban mosaic vary in size and can be understood as ecosystems. On a higher-order spatial scale, dense villages, cities, suburbs, exurbs, and towns, constitute ecosystems (McGrath and Pickett 2011; McGrath and Shane 2017). Many urban ecosystems have grown to encompass large regions (United Nations 2006; Hahs 2016; McHale et al. 2018). Urban ecosystems are of growing importance globally, given that most of the world's population lives in places defined as urban and that population will continue to grow rapidly. Therefore, urban ecosystems are crucial for achieving the SDG (McPhearson et al. 2016).

Urban ecosystems are of a special kind, in which human artifacts and modifications of biota, and landforms, along with their control of the flows of energy, matter, and information predominate (Cadenasso et al. 2006b). Urban ecosystems are a distinctive ecosystem type, in which humans are the dominant, but not the only, agents of change (Collins et al. 2000; Grimm et al. 2000; Alberti 2005) where humans and biophysical phenomena together are co-producers of ecosystem functions (Alberti 2016; Rademacher et al. 2019). This co-production is the result of urbanization and continued urban change, which is a complex of distinctive physio-chemical, cultural, social, and economic processes. Urbanization produces diverse spatial patterns of urban development, profoundly affecting ecosystem functions, driven by land cover change and habitat modifications (Alberti 2005). Urban development patterns have the capacity to fragment, isolate, and degrade nearby natural ecosystems, by simplifying and homogenizing species composition, by disrupting or modifying fundamental ecological processes such as material, water, and energy exchange, flows, and transformations, by introducing invasive species and by injecting contaminants and pollutants in regional air and water plumes (Pickett and Cadenasso 2009; Forman 2016). This myriad of interactions therefore can alter ecosystem functions both within and beyond urban ecosystems (Alberti 2005).

The term function has been widely applied in urban studies as well. Because urban systems are spatially complex and coproduced, function can have different meanings. Function may be assessed in non-normative ways to assess what the urban system does and what processes take place within it. For instance, in urban climatology, function has been defined as "the underlying uses and processes that shape a city, including its land use, its economy, and the cycles of the urban metabolism, which operate over different time scales" (Oke et al. 2017: 483). Using the metabolism approach, urban ecosystem functions have also been explored as stocks and flows of energy and materials (Inostroza 2014). However, given that humans, including individuals, households, institutions, etc., are parts of urban ecosystems, there is a widespread use of the term function in the sense of services (Childers et al. 2015). Because the "purposes" or human constituents in cities are so diverse and relevant, it is necessary to acknowledge that urban (ecosystem) functions have a double meaning. An example for a non-normative understanding of function is urban metabolism, whereas urban biodiversity functions, environmental justice functions, water quality functions, climate mitigation function, or resilience to disturbances are examples for a normative understanding. In many cases the diverse conceptualizations of functions may conflict leading to the fact that the co-produced ecosystem functions of diverse, extensive, and changing urban systems must be negotiated in light of power, justice, and alternative futures (McHale et al. 2018; Cadenasso and Pickett 2018).

Ecosystem Functions and Sustainability of Life on Land

Most ecosystems of the Earth have experienced an extensive resource use and exploitation. During the last century, the state of life on land reached critical thresholds, facing extinctions, increasing biodiversity lost and resource depletion. A more nuanced and careful approach to the use of ecosystems and resources is necessary to ensure sustainability of life on land. Landscape change and urbanization have a tremendous impact on life and the ecosystem. Landscapes are rapidly changing due to human action, while urbanization is increasing its pace in most regions of the globe.

The understanding, analysis, measurement, and modeling of ecosystem functions can provide the necessary scientific basis to pursue successful implementation for several SDG:

15.1 Conserve and Restore Terrestrial and Freshwater Ecosystems

By 2020, ensure the conservation, restoration, and sustainable use of terrestrial and inland freshwater ecosystems and their services, in particular forests, wetlands, mountains, and drylands, in line with obligations under international agreements.

15.2 End Deforestation and Restore Degraded Forests

By 2020, promote the implementation of sustainable management of all types of forests, halt deforestation, restore degraded forests, and substantially increase afforestation and reforestation globally.

15.4 Ensure Conservation of Mountain Ecosystems

By 2030, ensure the conservation of mountain ecosystems, including their biodiversity, in order to enhance their capacity to provide benefits that are essential for sustainable development.

15.5 Protect Biodiversity and Natural Habitats

Take urgent and significant action to reduce the degradation of natural habitats, halt the loss of biodiversity, and, by 2020, protect and prevent the extinction of threatened species.

15.9 Integrate Ecosystem and Biodiversity in Governmental Planning

By 2020, integrate ecosystem and biodiversity values into national and local planning, development processes, poverty reduction strategies, and accounts.

Cross-References

▶ Ecological Integrity
▶ Ecosystem Services

References

Alberti M (2005) The effects of urban patterns on ecosystem function. Int Reg Sci Rev 28:168–192. https://doi.org/10.1177/0160017605275160

Alberti M (2016) Cities that think like planets: complexity, resilience, and innovation in hybrid ecosystems. University of Washington Press, Seattle

Balvanera P, Kremen C, Martinez-Ramos M (2005) Applying community structure analysis to ecosystem function: examples from pollination and carbon storage. Ecol Appl 15:360–375

Bastian O, Steinhardt U (2002) Development and perspectives of landscape ecology. Kluwer, Dordrecht

Bennett EM, Peterson GD, Gordon LJ (2009) Understanding relationships among multiple ecosystem services. Ecol Lett 12:1394–1404. https://doi.org/10.1111/j.1461-0248.2009.01387.x

Cadenasso ML, Pickett STA (2018) Situating sustainability from an ecological science perspective. In: Sze J (ed) Sustainability: approaches to environmental justice and social power. New York University Press, New York, pp 29–52

Cadenasso ML, Pickett STA, Grove JM (2006a) Dimensions of ecosystem complexity: heterogeneity, connectivity, and history. Ecol Complex 3:1–12. https://doi.org/10.1016/j.ecocom.2005.07.002

Cadenasso ML, Pickett STA, Grove MJ (2006b) Integrative approaches to investigating human-natural systems: the Baltimore ecosystem study. Nat Sci Soc 14:4–14. https://doi.org/10.1051/nss:2006002

Cardinale BJ, Matulich KL, Hooper DU et al (2011) The functional role of producer diversity in ecosystems. Am J Bot 98:572–592. https://doi.org/10.3732/ajb.1000364

Chapin SF, Power ME, Cole JJ (2011) Coupled biogeochemical cycles and Earth stewardship. Front Ecol Environ 9:3. https://doi.org/10.1890/1540-9295-9.1.3

Childers DL, Cadenasso ML, Morgan Grove J et al (2015) An ecology for cities: a transformational nexus of design and ecology to advance climate change resilience and urban sustainability. Sustainability 7:3774–3791. https://doi.org/10.3390/su7043774

Collins JP, Kinzig A, Grimm NB et al (2000) A new urban ecology. Am Sci 88:416–425. https://doi.org/10.1511/2000.5.416

Cortinovis C, Geneletti D (2018) Ecosystem services in urban plans: what is there, and what is still needed for better decisions. Land Use Policy 70:298–312. https://doi.org/10.1016/j.landusepol.2017.10.017

Costanza R, Fisher B, Mulder K et al (2007) Biodiversity and ecosystem services: a multi-scale empirical study of the relationship between species richness and net primary production. Ecol Econ 61:478–491. https://doi.org/10.1016/j.ecolecon.2006.03.021

de Groot R (1992) Functions of nature: evaluation of nature in environmental planning, management and decision making. Wolters Noordhoff, Groningen

de Groot RS, Wilson MA, Boumans RMJ (2002) A typology for the classification, description and valuation of ecosystem functions, goods and services. Ecol Econ 41:393–408

De Groot RS, Fisher B, Christie M, Aronson J, Braat L, Haines-Young R, Gowdy J, Maltby E, Neuville A, Polasky S, Portela R, Ring I (2010) Integrating the ecological and economic dimensions in biodiversity and ecosystem service valuation. Chapter 1 (pp 9-40) In: TEEB (2010) The Economics of Ecosystems and Biodiversity: Ecological and Economic Foundations. Edited by Pushpam Kumar, Earthscan, London and Washington. ISBN 9781849712125

De Groot RS, Brander L, van der Ploeg S, Costanza R, Bernard F, Braat L, Christie M, Crossman N, Ghermandi A, Hein L, Hussain S, Kumar P, McVittie A, Portela R, Rodriguez LC, ten Brink P, van Beukering P (2012) Global estimates of the value of ecosystems and their services in monetary units. Ecosystem Services 1:50–61

Forman RTT (2016) Urban ecology principles: are urban ecology and natural area ecology really different? Landsc Ecol 31:1653–1662. https://doi.org/10.1007/s10980-016-0424-4

Forman R, Godron M (1986) Landscape ecology. Wiley, New York

Gómez-Baggethun E, de Groot R, Lomas PL, Montes C (2010) The history of ecosystem services in economic theory and practice: from early notions to markets and payment schemes. Ecol Econ 69:1209–1218. https://doi.org/10.1016/j.ecolecon.2009.11.007

Grimm NB, Grove JM, Pickett STA, Redman CL (2000) Integrated approaches to long-term studies of urban ecological systems. Bioscience 50:571–584. https://doi.org/10.1007/978-0-387-73412-5_8

Hahs AK (2016) Urban megaregions and the continuum of urbanity – embracing new frameworks or extending the old? Ecosyst Health Sustain 2:1–2. https://doi.org/10.1002/ehs2.1201

Haines-young R, Potschin M (2017) The classification challenge. In: Burkhard B, Maes J (eds) Mapping Ecosystem Services. PENSOFT Publishers, Sofia, pp 42–45

Haines-Young R, Potschin M (2018) Common International Classification of Ecosystem Services (CICES) V5. 1. Guidance on the Application of the Revised Structure. Nottingham

Hansen R, Frantzeskaki N, McPhearson T et al (2015) The uptake of the ecosystem services concept in planning discourses of European and American cities. Ecosyst Serv 12:228–246. https://doi.org/10.1016/j.ecoser.2014.11.013

Hector A, Joshi J, Scherer-Lorenzen M et al (2007) Biodiversity and ecosystem functioning: reconciling the results of experimental and observational studies. Funct Ecol 21:998–1002. https://doi.org/10.2307/1313535

Helliwell DR (1969) Valuation of wildlife resources. Reg Stud 3:41–47. https://doi.org/10.1080/09595236900185051

Inostroza L (2014) Measuring urban ecosystem functions through 'Technomass' – a novel indicator to assess urban metabolism. Ecol Indic 42:10–19. https://doi.org/10.1016/j.ecolind.2014.02.035

Jax K (2005) Function and 'functioning' in ecology: what does it mean? Oikos 111:641–648

La Notte A, D'Amato D, Mäkinen H et al (2017) Ecosystem services classification: a systems ecology

perspective of the cascade framework. Ecol Indic 74:392–402. https://doi.org/10.1016/j.ecolind.2016.11.030
Liu Y, Li T, Zhao W et al (2019) Landscape functional zoning at a county level based on ecosystem services bundle: methods comparison and management indication. J Environ Manag 249. https://doi.org/10.1016/j.jenvman.2019.109315
Loreau M, Naeem S, Inchausti P (eds) (2002) Biodiversity and ecosystem functioning: synthesis and perspectives. Oxford University Press, Oxford
McGrath B, Pickett STA (2011) The metacity: a conceptual framework for integrating ecology and urban design. Challenges 2:55–72. https://doi.org/10.3390/challe2040055
McGrath B, Shane G (2017) Metropolis, megalopolis and metacity. In: Crysler CG, Cairns S, Heynen H (eds) The Sage handbook of architectural theory. SAGE, London, pp 641–657
McHale MR, Beck SM, Pickett STA et al (2018) Democratization of ecosystem services – a radical approach for assessing nature's benefits in the face of urbanization. Ecosyst Health Sustain 4:115–131. https://doi.org/10.1080/20964129.2018.1480905
McPhearson T, Haase D, Kabisch N, Gren Å (2016) Advancing understanding of the complex nature of urban systems. Ecol Indic 70:566–573. https://doi.org/10.1016/j.ecolind.2016.03.054
Odum HT (1994) Ecological and general systems: an introduction to systems ecology. University Press of Colorado, Niwot
Odum EP, Odum HT (1972) Natural areas as necessary components of man's total environment. Trans North Am Wildl Nat Res Conf 37:178–189
Oke TR, Mills G, Christen A, Voogt JA (2017) Urban climates. Cambridge University Press, Cambridge
Pickett STA, Cadenasso ML (2002) The ecosystem as a multidimensional concept: meaning, model, and metaphor. Ecosystems 5:1–10. https://doi.org/10.1007/s10021-001-0051-y
Pickett STA, Cadenasso ML (2009) Altered resources, disturbance, and heterogeneity: a framework for comparing urban and non-urban soils. Urban Ecosyst 12:23–44. https://doi.org/10.1007/s11252-008-0047-x
Potschin M, Haines-young R (2016) Conceptual frameworks and the cascade model. In: Potschin M, Jax K (eds) OpenNESS Ecosystem Services Reference Book. EC FP7 Grant Agreement no. 308428, pp 1–6
Rademacher A, Cadenasso ML, Pickett STA (2019) From feedbacks to coproduction: toward an integrated conceptual framework for urban ecosystems. Urban Ecosyst 22:65–76. https://doi.org/10.1007/s11252-018-0751-0
Rapport DJ (1992) Evaluating ecosystem health. J Aquat Ecosyst Health 1:15–24. https://doi.org/10.1007/BF00044405
Rieb JT, Chaplin-Kramer R, Daily GC et al (2017) When, where, and how nature matters for ecosystem services: challenges for the next generation of ecosystem service models. Bioscience 67:820–833. https://doi.org/10.1093/biosci/bix075
Rose KC, Graves RA, Hansen WD et al (2017) Historical foundations and future directions in macrosystems ecology. Ecol Lett 20:147–157. https://doi.org/10.1111/ele.12717
Spake R, Lasseur R, Crouzat E et al (2017) Unpacking ecosystem service bundles: towards predictive mapping of synergies and trade-offs between ecosystem services. Glob Environ Chang 47:37–50. https://doi.org/10.1016/j.gloenvcha.2017.08.004
Syrbe R, Bastian O, Matthias R, James P (2007) A framework for monitoring landscape functions: the Saxon Academy Landscape Monitoring Approach (SALMA), exemplified by soil investigations in the Kleine Spree floodplain, Saxony, vol 79, pp 190–199. https://doi.org/10.1016/j.landurbplan.2006.02.005
United Nations (2006) State of the world's cities 2006/7. United Nations Human Settlements Programme. UN Habitat, Nairobi
Weathers KC, Groffman PM, Van Dolah E et al (2016) Frontiers in ecosystem ecology from a community perspective: the future is boundless and bright. Ecosystems 19:753–770. https://doi.org/10.1007/s10021-016-9967-0
Wiggering H, Dalchow C, Glemnitz M et al (2006) Indicators for multifunctional land use – linking socio-economic requirements with landscape potentials. Ecol Indic 6:238–249. https://doi.org/10.1016/j.ecolind.2005.08.014
Willemen L, Verburg PH, Hein L, van Mensvoort MEF (2008) Spatial characterization of landscape functions. Landsc Urban Plan 88:34–43. https://doi.org/10.1016/j.landurbplan.2008.08.004