

Chapter 5

A Network Approach to Green Infrastructure: How to Enhance Ecosystem Services Provision?



Andrea Staccione, Sebastian Candiago, and Jaroslav Mysiak

Significance Statement Landscape fragmentation is increasingly undermining the capacity of ecosystems to provide services and benefits to humans. The development of a green infrastructure network can enhance the provision of ecosystem services connecting ecosystem features. We review and explore the concepts, methodologies, and applications that allow to analyse connectivity of green infrastructure networks and the role of spatial connectivity for supporting and maintaining ecosystem services. Together with connectivity, the quality, quantity, diversity, redundancy, and distances of ecosystem elements result to be important characteristics to support the provision of services. We report how spatial and connectivity-based methodologies (for example, network indices and spatial pattern analysis) can support characterisation and prioritization of green infrastructure networks for crucial interventions, both for preserving and restoring connection elements.

Keywords Landscape connectivity · Nature-based solutions · Habitat fragmentation · Network analysis · Spatial planning

1 Introduction

Natural and semi-natural ecosystems are threatened by landscape changes. The fragmentation of contiguous areas of natural ecosystems into smaller elements, driven by urban sprawl and population growth, is one of the main pressures for environmental quality. It is expected that 68% of the global human population will live in cities by 2050, with nearly the 90% of increase occurring in Asia and Africa,

A. Staccione · J. Mysiak

Euro-Mediterranean Center on Climate Change, Venice, Italy

Ca' Foscari University of Venice, Venice, Italy

S. Candiago (✉)

Institute for Alpine Environment, Eurac Research, Bolzano/Bozen, Italy

Ca' Foscari University of Venice, Venice, Italy

e-mail: sebastian.candiago@eurac.edu

© The Author(s) 2022

I. Misiune et al. (eds.), *Human-Nature Interactions*,
https://doi.org/10.1007/978-3-031-01980-7_5

and the urban population of high-income countries is expected to rise from 81% to 88% by the mid-century (UN, 2018). These trends will contribute to increasing landscape fragmentation and degradation of ecosystems (EC, 2015). At the current trend of soil sealing, Europe, for example, will lose up to 10–15% of the beneficial value produced by ecosystems by 2050 (Maes et al., 2015).

Ecosystem services (ES), i.e. the benefits that people obtain from nature, are intensely affected by landscape fragmentation since they depend on ecological functions, landscape spatial pattern distribution, and organisms and material movements (Mitchell et al., 2013). Landscape patterns and ecological functions are strictly related. A change in landscape configuration leads to changes in ecosystem connectivity, defined as the degree to which the landscape influences species movements across ecosystems (Taylor et al., 1993). Fragmentation causes habitat loss and isolation of species, making them more vulnerable and less resilient to changes (Field & Parrott, 2017). Connectivity is fundamental for maintaining species dispersal and sustaining ecological processes. A decrease of connectivity has negative impacts on ES provision, by affecting the rate and pattern of biotic and abiotic flows, the habitats and populations dimension, and, indirectly, altering biodiversity and ecological functions (Mitchell et al., 2013, 2015).

Strategies based on the usage of ecosystem functions to increase environmental, social, and economic benefits, the so-called nature-based solutions, are gaining importance as preferable options when addressing climate and environmental challenges (EC, 2015). These ecosystem-based approaches have a positive effect on the environment, biodiversity and provision of ES. Green infrastructure (GI) is a “strategically planned network” of natural and semi-natural areas with other environmental features designed and managed to simultaneously deliver a wide range of ES and multiple benefits to the society (EC, 2013). GI may mitigate natural hazards by mediating flow and nuisances, or through maintenance of stable physical, chemical, and biological conditions, for example wetlands and floodplains acting as buffers against floods, well-managed forests reducing the risk of landslides, green urban areas mitigating extremely high temperatures.

GI plays an important role for harvesting the effects of spatial configuration and composition on ecological changes and the provision of ES. GI builds upon interconnections, spatial interactions, and distributions of natural elements across a landscape. Therefore, GI can be used to plan and design green spaces, protected areas, and ecosystem restoration from a network perspective. To do this, GI can be described as a set of core areas, hotspots of services and benefits, such as protected areas, forests, urban green spaces or floodplains, and corridors, as vegetated buffer strips, green alleys, or hedgerows that connect core areas to each other and to humans. Core areas and corridors can be respectively translated into nodes and links in a network language. Taking elements from landscape ecology, graph and network analysis make it possible to quantify the effects of landscape fragmentation and to integrate these processes and relationships into GI spatial design and management to address environmental challenges (Babí Almenar et al., 2018). Planning GI as a network, while incorporating ecological, social, and economic aspects, can enhance landscape connectivity and be developed at different spatial scales, from neighbourhood, to cities, to regional, national and international scales (Lafortezza et al., 2013).

Recognising the relevance of GI configuration across the landscape, we explore how to plan and design a GI network for supporting the supply of ES and environmental quality. First, we discuss main concepts and aspects contributing to maintaining and improving ES provision through GI. Second, we review and summarise methodologies to analyse connectivity for GI, spanning from landscape ecology to spatial planning, graph, and network analysis. The chapter highlights elements that can support further developments of frameworks and strategies for territorial planning and decision-making processes.

2 What Matters for Ecosystem Services Enhancement?

The configuration and distribution of GI is fundamental for ensuring and enhancing ES provision. Studies on ES assessment highlight the need of mapping and characterizing ecosystem features. Improving landscape connectivity is important for maintaining ecosystem quality and resilience, meant as the capacity to sustain functions and services in face of disturbances and changes (Table 5.1). It implies the re-creation or restoration of green corridors or natural areas that can facilitate and allow species movements and services or material flows across the landscape. Together with connectivity, diversity and redundancy of ecosystem features have been identified as key characteristics for building resilience for ES against disturbances and changes in the socio-ecological system (Biggs et al., 2012). Diversity refers to the variety, balance, or disparity of elements within the system, leading to spatial and ecological heterogeneity. Diverse elements would respond differently to disturbances, influencing the spread of impacts on connectivity, ensuring that some landscape patches remain undisturbed and provide refuges for the provision of services. Redundancy is the replication of elements or pathways, guaranteeing a compensation in case of losses or failures. These features secure an insurance effect of connectivity, allowing network stability and robustness (Gonzalez et al., 2017). This requires particular attention to the central areas of the ecological networks, that can destabilize the network more rapidly if degraded or lost. Designing and planning a network of GI help to meet these requirements for ES provision and achieving

Table 5.1 Summary and definitions of the key concepts for ecosystem services enhancement

Term	Definition
Connectivity	Degree to which ecosystems features are structurally connected and influence the movements of organisms, material, and energy through the landscape.
Diversity	Presence of different types of ecosystem features across the landscape.
Redundancy	Presence of multiple similar ecosystem features across the landscape.
Proximity to humans	Distances of ecosystems features providing the services (supply sites) from human population using/benefitting from the services (demand sites).
Quality	Level of health of ecosystems that allow good ecological functioning and services provision.

good levels of biodiversity and environmental quality. Indeed, diverse ecosystems distributed across the landscape that are structurally and functionally connected, i.e. both in term of physical landscape structure itself and of organisms and material movements through this structure, demonstrate more stability and resilience compared to systems characterized by isolated components and by low-biodiversity environments (Field & Parrott, 2017).

Proximity to people, distances between habitats and ecosystem quality represent also important features for enhancing ES provision for spatial planning supported by ecological thinking. The definition and interrelationships of landscape character, services and values are essential (Babí Almenar et al., 2018). Vallecillo et al. (2016) demonstrated how urban and peri-urban areas can have equivalent ES potential to more remote and natural ecosystems, identifying however a lower potential per unit area in degraded ecosystems. The proximity to people has a positive influence on the benefits that ecosystems can generate as services, although it is not always necessary for their provision. Analysing the connectivity requirements for ES in spatial planning, Kukkala and Moilanen (2017) found that the ideal spatial configuration for ES may be influenced by the size of local supply areas and the regional network around that support ES provision, the flow between supply and demand sites for services and the access and distribution of ES to multiple stakeholders. For planning green networks, other important aspects are interactions, synergies, and trade-offs between services. Increasing the supply of one ES can either enhance or hamper the delivery of other services. Structure, location, and scope of intervention are therefore vital in planning potential GI network configuration for services and benefits gain.

3 Connectivity and Green Infrastructures: Collection of Methodologies

GI, understood in terms of core areas and corridors, can be represented by graphs and analysed with network measures, that are used to investigate the relationships and influences between GI elements (Fig. 5.1). Graph theory is a well-established mathematical approach dealing with problems of connectivity, network representation, flow and routing in networks applied to many fields. It found applications in landscape ecology studies for habitat and landscape connectivity analysis (Urban & Keitt, 2001). Graphs are used as models of landscapes, constituted by nodes typically representing habitat patches and by links that indicate a functional connection or dispersal potential. Initially applied to population analysis, their potential has been soon recognised for representing and analysing landscape structure through network measures (Galpern et al., 2011). Indeed, due to their flexibility and low data requirements, graphs can be applied to different landscape types and scales.

Graph and network analysis can highlight the favourable geographical configuration that should be maintained, restored, or built by human intervention in order to ensure diverse, redundant and connected ecosystem features of good quality. Using

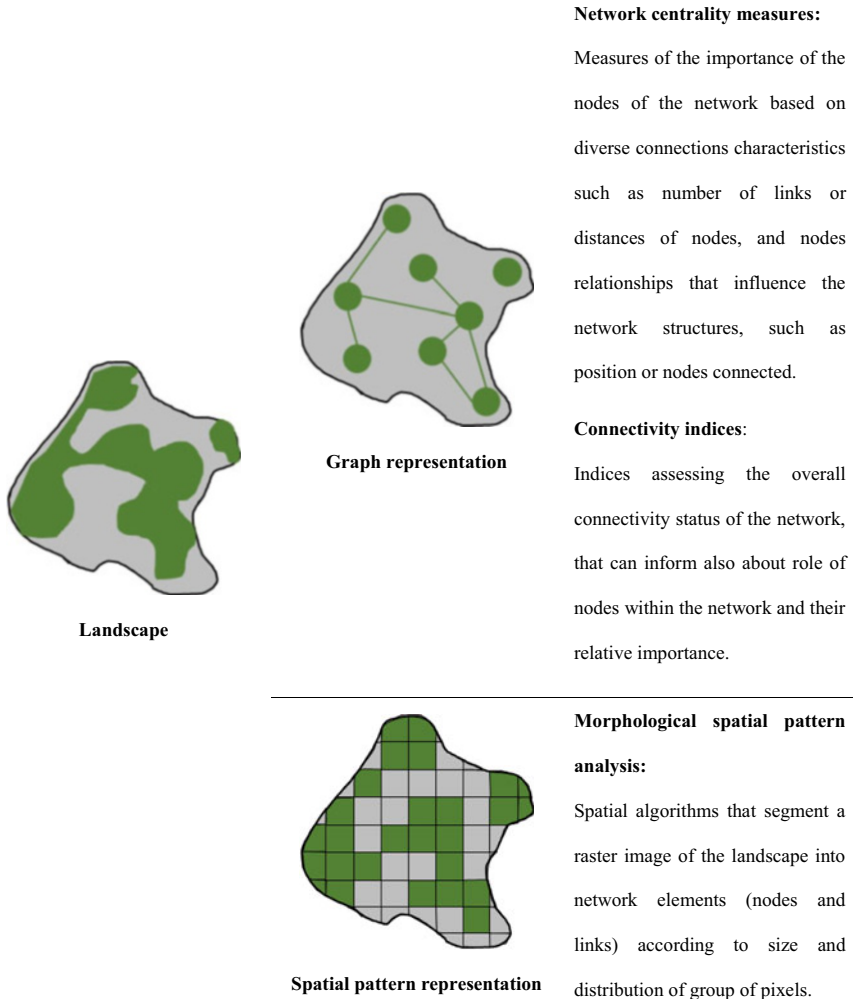


Fig. 5.1 Summary of main methodologies collected and key concepts visualisations

network centrality measures and connectivity indices enables to characterize the degree of connectivity of the landscape and to identify and rank the importance, role and contribution of nodes, and connections to the overall connectivity (Fenu & Pau, 2018). A main step is the definition of the landscape network structure and the characterization of existing components, i.e. groups of connected nodes or sub-network. It is then possible to identify cut-nodes that stabilize the network. Those nodes are the features that determine the separation of a connected component into two smaller components when removed and could maintain a network connected and stable over time.

To analyse the structure of networks and graphs, different measures or indices are available. These measures are often context dependent and their definition is not always straightforward. Network centrality measures, such as betweenness, degree and closeness centrality, are used to investigate the type and importance of contribution of individual nodes to the system (Field & Parrott, 2017). For spatial analysis, several landscape connectivity indices also exist and can be used for the same scope. The advantage of indices is that of generally taking into consideration the position, quality, and quantity of available areas, including both the effects of landscape composition and structure on species presence and movements (Avon & Bergès, 2016). Two examples of these indices are the Integral Index of Connectivity and the Probability of Connectivity (Saura & Pascual-Hortal, 2007). These indices are more sensitive to the changes affecting landscape configurations and can detect those areas most critical for conservation. Both are graph-based indices applicable to any type and scale of landscape, computing both the overall degree of connectivity and the relative importance of each node and connection. These indices can also be partitioned to assess the type of contributions of each node, in terms of intra-patch connectivity, potential dispersal flux and stepping-stones role (Saura & Rubio, 2010).

Indices can be used to include connectivity consideration when planning new interventions for GI improvement. To do this, connectivity assessment indices and models often consider structural landscape elements as a proxy for functional connectivity, as for example using the presence of a green corridor to measure species movements potential. This bears the risk of oversimplifying the reality. But if included in a wider, scalable and replicable framework assessing connectivity, they can better inform a more integrated landscape management and support practitioners and decision makers for future development plans. For example, Bolliger and Silbernagel (2020) explored the contribution of connectivity assessment methods for a successful spatial design and implementation of GI, stressing the contribution of GI both on structural and functional connectivity to identify critical area of intervention, both for preserving or restoring connection elements. The structural connectivity is usually analysed by addressing the presence and absence of connections, the configuration of corridors and stepping-stones elements, their distances, area and amount of habitat and connections (Kindlmann & Burel, 2008). Functional connectivity analysis is more based on the probability of moving between areas, dispersal rate, search time and the number of areas. In planning perspective, functional and structural corridors are the key for material and species flows, enough to be considered fragile elements and bottlenecks of concerns. The analysis of existing network structure and the identification of critical areas can help to find space and needs of network improvement. Improvement of the network can follow or combine two perspectives: the site-centre and the system-centric perspective (Zetterberg et al., 2010). They respectively aim to identify critical isolated nodes in order to restore connections to them, and to identify the crucial regions for network structure where connectivity should be improved to benefit the overall resilience of the system. For GI design and implementation this is crucial to plan and prioritize where to intervene.

GI studies often apply connectivity concepts, perspectives, and indices using spatial analysis software and techniques such as Geographic Information System or alternative spatial-based approaches. An example is given by the combination of landscape connectivity indices with the morphological spatial pattern analysis (MSPA) (Saura et al., 2011). MSPA allows the characterization of the structure of the landscape network at binary pixel level, based on mathematical analysis of landscape configurations (Soille & Vogt, 2009). Landscape connectivity indices applied together with spatial pattern analysis have been proposed to study ecological networks at different scales, both regional and local, at different ecosystem types, to assess the current situation and to develop or restore connections. Different methods and tools are used jointly for assessing connectivity and simplifying the environmental management. This allows the comprehensive study of landscape structure characteristics through available limited data and generally open and free software. There are various software and tools available for spatial pattern and connectivity analysis (see for example McGarigal et al., 2012; Saura & Tornè, 2010; Vogt & Riitters, 2017; Watts et al., 2009), but not all have ready-to-use and well-integrated outputs and routines to be combined with graph-based connectivity analysis and indices.

The conceptualization of GI as a network and the application of a set of network indicators to analyse its structure is increasing in the research field to foster the understanding of spatial needs for ES delivery. Research can inform policy and decision-making for managing and enhancing biodiversity and ES in a more holistic way. Liqueste et al. (2015), for example, integrated the capacity to deliver ES with the identification of core habitats and corridors, based on mapping and connectivity methods, to inform a meaningful development of GI network at EU level. This allows contributions for conservation and/or restoration goals within EU policies. Similarly, Maes et al. (2015) investigated how an expansion of the GI network across the EU would help to maintain ES level, estimating a need of about 20,000 km² of additional GI to maintain ES at 2010 levels: an increase of 2.2% in the share of GI area would be needed to face any additional percentage of artificial land. Ala-Hulkko et al. (2019) used combined network and mapping analysis to study the supply and demand of ES across Europe, showing an unbalanced distribution of ES supply and demand sites. Methodologies and results can help to identify where investments, both in terms of natural infrastructure, restoration and eventually transport, are more needed.

4 Conclusion

In this chapter, we reviewed concepts, methodologies, and applications that allow to analyse connectivity of GI networks and the role of spatial connectivity for supporting and maintaining ES. Connectivity is a fundamental condition enabling species dispersal and fostering ES provision. Ecosystems quality, distances, diversity and quantity have also been identified as important design characteristics. An

efficient design and planning of GI help to prioritize areas where intervention for restoration and preservation of connectivity are more urgent for ES. Spatial and connectivity-based methodologies resulted to be appropriate to characterise the network structure and inform about overall connectivity status, most important nodes, isolated and poor connected areas. This allows to identify where and how the network can be improved taking into consideration types and quantity of nodes and connections required to ensure ecosystem resilience to environmental and ongoing climatic changes. Easy and replicable graph-based methods can be used to inform landscape managers by developing conceptual frameworks and strategies that can support them through the overall process of GI network analysis and plan: from the identification of network elements to the assessment of current condition of connectivity to the planification of future network configuration. Spatial information and landscape-based contributions can support the realization of nature-based solutions, considering location, societal challenges, alternative intervention, and their impacts to be effective also in future climate change conditions.

References

- Ala-Hulkko, T., Kotavaara, O., Alahuhta, J., & Hjort, J. (2019). Mapping supply and demand of a provisioning ecosystem service across Europe. *Ecological Indicators*, *103*, 520–529. <https://doi.org/10.1016/J.ECOLIND.2019.04.049>
- Avon, C., & Bergès, L. (2016). Prioritization of habitat patches for landscape connectivity conservation differs between least-cost and resistance distances. *Landscape Ecology*, *31*(7), 1551–1565. <https://doi.org/10.1007/s10980-015-0336-8>
- Babí Almenar, J., Rugani, B., Geneletti, D., & Brewer, T. (2018). Integration of ecosystem services into a conceptual spatial planning framework based on a landscape ecology perspective. *Landscape Ecology*, *33*(12), 2047–2059. <https://doi.org/10.1007/s10980-018-0727-8>
- Biggs, R., Schi, M., Biggs, D., Bohensky, E. L., Burnsilver, S., Cundill, G., Dakos, V., Daw, T. M., Evans, L. S., Kotschy, K., Leitch, A. M., Meek, C., Quinlan, A., Raudsepp-Heame, C., Robards, M. D., Schoon, M. L., Schultz, L., & West, P. C. (2012). Toward principles for enhancing the resilience of ecosystem services. *Annual Review of Environment and Resources*, *37*, 421–448. <https://doi.org/10.1146/annurev-environ-051211-123836>
- Bolliger, J., & Silbernagel, J. (2020). Contribution of connectivity assessments to green infrastructure (GI). *ISPRS International Journal of Geo-Information*, *9*(4). <https://doi.org/10.3390/ijgi9040212>
- EC: COM. (2013). *249 final: Green Infrastructure (GI) — Enhancing Europe's Natural Capital*.
- EC. (2015). *Towards an EU research and innovation policy agenda for nature-based solutions & re-Naturing cities*.
- Fenu, G., & Pau, P. L. (2018). Connectivity analysis of ecological landscape networks by cut node ranking. *Applied Network Science*, *3*(22). <https://doi.org/10.1007/s41109-018-0085-0>
- Field, R. D., & Parrott, L. (2017). Multi-ecosystem services networks: A new perspective for assessing landscape connectivity and resilience. *Ecological Complexity*, *32*, 31–41. <https://doi.org/10.1016/J.ECOCOM.2017.08.004>
- Galpern, P., Manseau, M., & Fall, A. (2011). Patch-based graphs of landscape connectivity: A guide to construction, analysis and application for conservation. *Biological Conservation*, *144*(1), 44–55. <https://doi.org/10.1016/j.biocon.2010.09.002>
- Gonzalez, A., Thompson, P., & Loreau, M. (2017). Spatial ecological networks: Planning for sustainability in the long-term. *Current Opinion in Environment Sustainability*, *29*, 187–197. <https://doi.org/10.1016/J.COSUST.2018.03.012>

- Kindlmann, P., & Burel, F. (2008). Connectivity measures: A review. *Landscape Ecology*, 23(8), 879–890. <https://doi.org/10.1007/s10980-008-9245-4>
- Kukkala, A. S., & Moilanen, A. (2017). Ecosystem services and connectivity in spatial conservation prioritization. *Landscape Ecology*, 32(1), 5–14. <https://doi.org/10.1007/s10980-016-0446-y>
- Laforteza, R., Davies, C., Sanesi, G., & Konijnendijk, C. C. (2013). Green Infrastructure as a tool to support spatial planning in European urban regions, iForest. *Biogeosciences Forest*, 6(3), 102. <https://doi.org/10.3832/IFOR0723-006>
- Liquete, C., Kleeschulte, S., Dige, G., Maes, J., Grizzetti, B., Olah, B., & Zulian, G. (2015). Mapping green infrastructure based on ecosystem services and ecological networks: A pan-European case study. *Environmental Science & Policy*, 54, 268–280. <https://doi.org/10.1016/J.ENVSCI.2015.07.009>
- Maes, J., Barbosa, A., Baranzelli, C., Zulian, G., Batista e Silva, F., Vandecasteele, I., Hiederer, R., Liquete, C., Paracchini, M. L., Mubareka, S., Jacobs-Crisioni, C., Castillo, C. P., & Lavalle, C. (2015). More green infrastructure is required to maintain ecosystem services under current trends in land-use change in Europe. *Landscape Ecology*, 30(3), 517–534. <https://doi.org/10.1007/s10980-014-0083-2>
- McGarigal, K., Cushman, S., & Ene, E. (2012). FRAGSTATS v4: Spatial Pattern Analysis Program for Categorical and Continuous Maps., [online] Available from: <http://www.umass.edu/landeco/research/fragstats/fragstats.html>
- Mitchell, M. G. E., Bennett, E. M., & Gonzalez, A. (2013). Linking landscape connectivity and ecosystem service provision: Current knowledge and research gaps. *Ecosystems*, 16(5), 894–908. <https://doi.org/10.1007/s10021-013-9647-2>
- Mitchell, M. G. E., Suarez-Castro, A. F., Martinez-Harms, M., Maron, M., McAlpine, C., Gaston, K. J., Johansen, K., & Rhodes, J. R. (2015). Reframing landscape fragmentation's effects on ecosystem services. *Trends in Ecology & Evolution*, 30(4), 190–198. <https://doi.org/10.1016/J.TREE.2015.01.011>
- Saura, S., & Pascual-Hortal, L. (2007). A new habitat availability index to integrate connectivity in landscape conservation planning: Comparison with existing indices and application to a case study. *Landscape and Urban Planning*, 83(2–3), 91–103. <https://doi.org/10.1016/J.LANDURBPLAN.2007.03.005>
- Saura, S., & Rubio, L. (2010). A common currency for the different ways in which patches and links can contribute to habitat availability and connectivity in the landscape. *Ecography (Cop.)*, 33(3), 523–537. <https://doi.org/10.1111/j.1600-0587.2009.05760.x>
- Saura, S., & Tornè, J. (2010). Conefor 2.6 user manual, [online] Available from: www.conefor.org.
- Saura, S., Vogt, P., Velázquez, J., Hernando, A., & Tejera, R. (2011). Key structural forest connectors can be identified by combining landscape spatial pattern and network analyses. *Forest Ecology and Management*, 262, 150–160. <https://doi.org/10.1016/j.foreco.2011.03.017>
- Soille, P., & Vogt, P. (2009). Morphological segmentation of binary patterns. *Pattern Recognition Letters*, 30(4), 456–459. <https://doi.org/10.1016/J.PATREC.2008.10.015>
- Taylor, P. D., Fahrig, L., Henein, K., & Merriam, G. (1993). Connectivity is a vital element of landscape structure. *Oikos*, 68(3), 571–573. <https://doi.org/10.2307/3544927>
- UN: World Urbanization Prospects: the 2018 revision (ST/ESA/SER.A/420), Department., New York. [online] Available from: <https://population.un.org/wup/Publications/Files/WUP2018-Report.pdf>, 2018.
- Urban, D. L., & Keitt, T. (2001). Landscape connectivity: A graph-theoretic perspective. *Ecology*, 82(5), 1205–1218. [https://doi.org/10.1890/0012-9658\(2001\)082\[1205:LCAGTP\]2.0.CO;2](https://doi.org/10.1890/0012-9658(2001)082[1205:LCAGTP]2.0.CO;2)
- Vallecillo, S., Polce, C., Barbosa, A., Perpiña Castillo, C., Vandecasteele, I., Rusch, G. M. and Maes, J.: Spatial alternatives for green infrastructure planning across the EU: An ecosystem service perspective, *Landscape and Urban Planning*, 174(December 2016), 41–54, doi:<https://doi.org/10.1016/j.landurbplan.2018.03.001>, 2018.
- Vogt, P., & Riitters, K. (2017). GuidosToolbox: Universal digital image object analysis. *European Journal of Remote Sensing*, 50(1), 352–361. <https://doi.org/10.1080/22797254.2017.1330650>
- Watts, M. E., Ball, I. R., Stewart, R. S., Klein, C. J., Wilson, K., Steinback, C., Lourival, R., Kircher, L., & Possingham, H. P. (2009). Marxan with zones: Software for optimal conservation

based land- and sea-use zoning. *Environmental Modelling & Software*, 24(12), 1513–1521. <https://doi.org/10.1016/j.envsoft.2009.06.005>

Zetterberg, A., Mörtberg, U. M., & Balfors, B. (2010). Making graph theory operational for landscape ecological assessments, planning, and design. *Landscape and Urban Planning*, 95, 181–191. <https://doi.org/10.1016/j.landurbplan.2010.01.002>

Open Access This chapter is licensed under the terms of the Creative Commons Attribution 4.0 International License (<http://creativecommons.org/licenses/by/4.0/>), which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license and indicate if changes were made.

The images or other third party material in this chapter are included in the chapter's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the chapter's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder.

