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Discussion

Multi-ecosystem services networks: A new perspective for assessing landscape connectivity and resilience

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ABSTRACT

The sustainability of natural systems is dependent on ecosystem services (ES), the delivery of which would cease without strong connectivity among the ecological processes underlying their production. However, research on the connectivity between multiple ES is in its infancy. Preliminary studies have focused on the flows of individual ES, but research has yet to expand to incorporating the interactions and feedbacks that occur between several different types of ES, and how such complex relationships might influence landscape sustainability. Our objective is to present a viewpoint on how spatial network theory can be used to assess connectivity between *multiple* ES and landscape ecological resilience. We provide an overview of knowledge and gaps in the literature linking connectivity, networks and ES concepts. We propose a spatial network theory-based approach for the assessment of multi-ES interactions and flows, and present how ecological process flows can be used to develop spatially explicit network nodes and links between multiple ES across landscapes. To illustrate our proposed approach, we provide a design framework and assessment of a simple conceptual multi-ES network. The use of multi-ES networks can help evolve our understanding of landscape connectivity and resilience, and incorporate complex ES relationships into applied planning and management programs.

1. Introduction

No human could exist without the services ecosystems provide. However, we too often neglect the responsibility of maintaining the ability of our landscapes to provide these services. With ever-increasing immigration of people into urban centres, human culture is increasingly disconnected from nature, even though our societies and economies are integral components of interconnected ecological landscapes (Moberg and Hauge Simonsen, 2014). To sustain ecological systems in the future, societies must reconnect and rebuild our appreciation of the importance of natural landscapes to our well-being and survival. Researchers participating in this paradigm shift need to recognize that such complex systems are built upon a myriad of interactions, which result in emergent dynamics equating to more than the sum of individual landscape components (Parrott and Meyer 2012; Woodward et al., 2013). Research should realign focus away from conducting isolated ecological assessments, and toward multidisciplinary study of how interconnectivity is key to the maintenance of natural landscapes. This viewpoint article outlines a novel interdisciplinary approach to the assessment of multi-ecosystem services (ES) connectivity and resilience across the landscape, which future research can use to deepen our understanding of the ecosystems that sustain us.

The concept of resilience has been increasingly applied to scientific approaches for assessing complex, interconnected systems (Moberg and Hauge Simonsen, 2014). We define 'resilience' as the long-term capacity of a system (e.g., a landscape) to deal with change while maintaining essentially the same structure and function, the same identity, without passing critical thresholds (Walker and Salt, 2012; Holling, 1973). Several properties contribute to system resilience, including adaptive capacity, diversity, redundancy, slow-changing variables, feedbacks, and connectivity (Biggs et al., 2012; Bennett et al., 2005; Parrott and Meyer 2012). In general, low resilience results in low-biodiversity landscapes that produce fewer ES and are more vulnerable to disturbance (Moberg and Hauge Simonsen, 2014). Maintaining landscape-scale resilience is increasingly cited as a goal of environmental management

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and planning strategies (e.g., Albert et al., 2014; MacDonald et al., 2014), however there exists no accepted method for measuring and assessing the ecological resilience of landscapes. Theory would suggest that an ecologically connected landscape that facilitates spatial movement of species and environmental flows should be more resilient than a fragmented landscape (Biggs et al., 2012; Lundberg and Moberg, 2003; Mitchell et al., 2013). We base our perspective on this premise, and describe how including ES connectivity in landscape assessment could facilitate quantitative, network-based analyses of landscape resilience.

Traditional landscape connectivity planning focuses on species habitat corridors, and current approaches in spatial ES research focus on mapping the distribution of ES provisioning (Egoh et al., 2008; Taylor et al., 1993), with recent studies assessing networks of individual ES and their flow across the landscape (e.g., Janssen et al., 2006; Fortuna et al., 2006; Heckmann and Schwanghart 2013; Phillips 2013; Peron et al., 2014). However, existing methods do not explore the variety of spatial interactions between multiple ES and how such interactions might impact landscape resilience. It is critical to confront this void, as we predict that landscape resilience is highly dependent upon the spatial quantity, quality, diversity, and redundancy of ES, as well as the cross-scale connectivity of the processes underlying their provisioning and management.

Although it has been suggested that managing *multiple* ES may be critical for supporting ecological resilience, there remains limited understanding of the factors that influence the spatial interactions between ES (Bennett et al., 2009; Mitchell et al., 2013; Qiu and Turner 2013, 2015). There is a call for more research on the mechanisms by which landscape connectivity influences provisioning of, access to, and benefits realized from ES, and on how relevant aspects might be measured (Mitchell et al., 2013). Conceptual theoretical frameworks have been suggested to help address these questions (Cumming et al., 2010; Gonzalez et al., 2011). These studies introduce the concept of exploring multi-node ecological networks within the context of links between meta-community functionality and ES provisioning, and present a framework for including both habitat and ecological interaction networks to assess their joint impact on biodiversity and associated ES, respectively. However, more work needs to be done toward designing landscape-scale networks that include multiple ES. Through these types of networks, we can begin to explore how ES interact with and influence one another across regional land use planning jurisdictions. Here, we present and test a novel approach for applying network theory to assess links between multiple ES across the landscape for improving our understanding, assessment, and management of landscape connectivity and resilience.

2. Linking concepts: connectivity, networks and ES

Landscape connectivity, which is the degree to which a landscape supports or inhibits ecological, hydrological, geomorphic, and human flows, is considered an essential characteristic of landscape structure and is vitally important to ecology, hydrology and geomorphology (Taylor et al., 1993; Phillips et al., 2015). Large, regional landscapes that are structurally and functionally connected demonstrate more robust self-organization, stability, hierarchy, and resilience compared to systems where components are isolated (Parrott and Meyer 2012; Cui et al., 2012); as such, quantifying connectivity is important for ecological conservation (Phillips et al., 2015).

In a spatial network, landscape elements such as habitat patches are represented as nodes, and links between the nodes may represent physical connections such as habitat corridors, or functional connections through species and gene dispersal, flow of water, or other exchanges between the nodes. The importance of connectivity for supporting resilience is dependent on the arrangement and strength of links across the landscape. Fundamentally, connectivity enables the transfer of material and information, which is critical for maintaining the ecosystem functions necessary for ES provisioning (Biggs et al., 2012). Further, connectivity supports resilience by supporting system recovery after disturbances (Nyström and Folke, 2001). The use of network-based methods to symbolize interactions between ES can support connectivity assessment and help to identify the spatial and temporal scales at which connectivity is relevant to ES provisioning.

2.1. ES networks in the literature

Recent research has applied spatial network theory methods to ES assessment, especially in the areas of water flow regulation (e.g., Fortuna et al., 2006; Poole et al., 2006; Cui et al., 2012, 2009; Heckmann and Schwanghart 2013; Phillips 2013), pests and disease (e.g., Margosian et al., 2009), seed dispersal networks (e.g., Janssen et al., 2006), and recreation (e.g., Shih, 2006). However, a similarity across all studies we reviewed was that they incorporated only one ES into network models and, although potential interactions with other ES were occasionally discussed, they were not explicitly represented or analyzed within the network (see also Cui et al., 2012). Such networks include a single type of node and link, and fail to incorporate the multipartite (i.e., different types of nodes) or multiplex (i.e., different types of links between nodes) characteristics (Horvát and Zweig, 2012), which are more representative of how complex networks function in the real world. Further, although ours was not a systematic review and therefore may not have captured all papers published on network theory applications to ES, the majority of studies we found focused on regulating ES. This points to several current gaps in the literature: the inclusion of *multiple ES types* (e.g., nodes representing water provisioning, soil formation, etc.) with *multiple types of connections between ES* (e.g., timber provisioning nodes provide pollinator habitat and evapotranspiration, with links to nearby agricultural and downslope water provisioning nodes, respectively) from *several ES categories* (i.e., provisioning, regulating, cultural) within the same network analysis.

In this viewpoint article, we address this gap by testing a new method for representing a multi-ES network using a fictional landscape. For this, we represent ES provisioning areas as network nodes, and identify their connectivity by interactions between ES and by mechanistic drivers of their spatial flows across a landscape. The resulting network represents multiple ES, and network centrality is examined to identify the ES nodes that contribute most to connectivity and, thus, landscape resilience. This simple example serves to demonstrate the potential of the method and its applicability to studying connectivity in real landscapes.

3. A new approach for multi-ES networks

The interactions and feedbacks between ES are influenced by multiple ecological components and processes across spatial and temporal scales (Qiu and Turner, 2013). Conceptualizing these properties is a daunting task, without even attempting to map, measure or empirically assess ES connectivity. Below we present an approach, building on ES mapping and modelling studies and rooted in network theory, to move toward addressing these complexities and to demonstrate how multiple ES can be represented in the context of landscape connectivity and resilience assessment.