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EDITORIAL

Advancing landscape sustainability science: theoretical foundation and synergies with innovations in methodology, design, and application

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Our society has entered in an era of Anthropocene, in which people and their activities dominate almost all ecosystems on the planet. In the context of growing uncertainties, landscape sustainability science (LSS), as a place-based, use-inspired science, aims to understand and improve the dynamic relationship between ecosystem services and human well-being. In this editorial, we identify the major theoretical foundations of LSS, discuss recent innovations in research methodology to advance LSS, summarize the extension of LSS through landscape design and geodesign, and examine the application of LSS for addressing sustainability challenges across multiple landscapes. We highlight that long-term regional sustainability can only be achieved by integrating context-based sustainability across agricultural, urban, and natural landscapes so as to minimize the regional ecological footprint and make advancement towards achieving the sustainable development goals.

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Introduction

Dramatic socioeconomic and environmental changes, including rising populations, escalating resource demands, shifting land uses, altering climate, and deteriorating pollution, have substantially transformed the landscapes and taken us beyond the bounds of human experience (Carpenter et al. 2009; Ellis 2015; Rockström et al. 2017). Recent research has indeed revealed that multiple fundamental life-sustaining processes, including climate change, loss of biological diversity, land system change, and altered biogeochemical cycles, have exceeded the limits within which human society can safely operate (Steffen et al. 2015). In face of these unprecedented anthropogenic landscape alterations, it is crucial to understand how to design, conserve, and manage our landscapes to sustainably provide ecosystem services that are essential for supporting human well-being now and into the future (Qiu et al. 2018a, b). Such research, management, and policy needs are at the core visions and concepts of LSS (Wu 2013), and are pivotal to achieving the sustainable development goals (SDGs) (Griggs et al. 2013).

This editorial is motivated by such landscape sustainability challenges, and arose out of the 7th Landscape Sustainability Science Forum at Qinghai Normal University on July 13–15, 2019. In this forum, scholars from around the world came together to present cutting-edge research on landscape sustainability, critically examine the state of knowledge from different disciplines, and collectively identify knowledge gaps in the broader LSS literature. Revolving around LSS, this editorial focuses on its theoretical foundations and synergies with innovations in methodology, design, and application (Fig. 1). We first identify theories that are fundamental to LSS, which is inherently interdisciplinary, multi-dimensional, multi-scaled, spatially-explicit, and place-based, that address the dynamic interactions and feedbacks in the coupled human–environmental systems. We then discuss the methodological innovations in research that improve our capabilities to investigate landscape patterns and dynamics. Next, we summarize how LSS informs landscape composition and configuration through landscape design and geo-design. At last, we examine the application of LSS across agricultural, urban, and natural landscapes towards achieving synergistic outcomes in food security, greenhouse gas emission mitigation, and environmental conservation.

Theoretical foundations

Sustainability science research has resulted in a rigorous set of the most fundamental and widely accepted concepts of sustainability that constitute the theoretical foundations for LSS (Wu and Hobbs 2002; Musacchio 2013; Wu 2013). LSS is built upon these

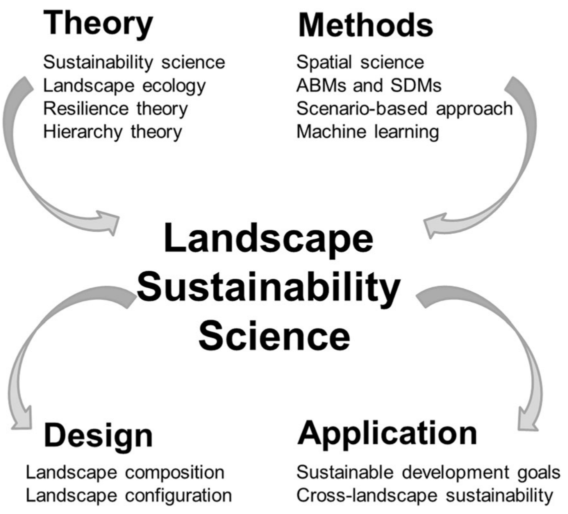

Fig. 1 Theoretical foundations of LSS, major methodological innovations to advance LSS, and extension of LSS through design and application

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concepts that include examples such as the *Brundtland definition* (i.e., meeting present needs without compromising future generations) (Brundtland et al. 1987), *triple bottom line* (i.e., simultaneous achievement of environmental, social, and economic goals) (Elkington 2013), and *weak vs. strong sustainability* (i.e., substitutability vs. complementarity of human-made capitals for natural capitals) (Daly 1995), *hierarchies of human needs and 'Daly Triangle'* (i.e., hierarchical framework in which nature is the 'ultimate means' to achieve 'ultimate needs' of human well-being), to more recent ecosystem services (Daily 1997) and nature's contribution to people (NCP) (Díaz et al. 2018) (i.e., nature's capacity to deliver benefits to humans). LSS embraces and enriches these key concepts in sustainability science in manners that (1) highlight the fundamental role of spatial heterogeneity; (2) alludes that landscape is the arguably 'optimal' scale to understand the dynamic relationships between society and nature, and achieve the sustainability of ecosystem services and human well-being; (3) stress the importance of cross-scale interactions and feedbacks for the resilience of landscapes to environmental changes; and (4) underlie the need of adaptive management, governance, and interventions to improve the reciprocal human-environment relationships across scales.

Landscape ecology also presents the important theoretical foundations for LSS. Landscape ecology is the science of studying interactions between spatial pattern and ecological processes. In other words, it addresses the causes and consequences of spatial heterogeneity—including landscape composition (type and amount) and landscape configuration (shape, connectivity and spatial arrangement)—across a range of scales (Turner 2005). LSS builds upon the concepts, theories and approaches from landscape ecology, but shifts from its traditionally more 'ecological' focus to the dynamics of social-ecological systems. Specifically, LSS focuses on understanding how ecological consequences of spatial heterogeneity (e.g., species, community, ecosystem functions) cascade to affect human well-being (e.g., basic material, freedom of choice, health, social relations, security, inequality) (MEA 2005), as well as impacts of social changes to natural systems (Qiu et al. 2018c). Given such distinctions, the concept of ecosystem services or NCP hence serve as one of the major bridges that links ecological changes to effects on human well-being, and also presents as the nexus between landscape ecology and LSS (Wu 2013). On this premise of this LSS framework, landscape patterns not only affect the biodiversity and ecosystem processes that underpin the production of ecosystem services, but also the demand and use through the flow of ecosystem services (Qiu 2019).

Resilience theory is another key concept essential to the development of LSS. Resilience was originally defined (in ecology) as the capacity of a system to absorb external stressors or disturbances without changing its fundamental structure and function, or shifting into a qualitatively different state (Holling 1973). In the past three decades, resilience has expanded from its original focus to the social-ecological systems and sustainability, in which it addresses the system's abilities to self-organize, adapt to change, and make transformations (Folke 2006). The resilience concept was further integrated with landscape ecology that leads to the development of landscape resilience (Cumming 2011). Landscape resilience highlights the critical importance of spatial heterogeneity, and spatial interactions among complex adaptive systems for overall resilience of systems to external drivers of change or disturbances. When applying to the social-ecological systems, landscape resilience differs from but contributes to LSS. In essence, resilience (or landscape resilience) is an inherent property of a complex system, and thus is non-normative and may not always be desirable (e.g., poverty trap as an undesirable resilience). In contrast, landscape sustainability is normative, and has specific sustainable outcomes (e.g., SDGs) that seek to address the major challenges facing human society while ensuring human well-being undiminished and the Earth systems un-degraded (Redman 2014). Hence, building and fostering desirable resilience of landscapes (e.g., through landscape design, planning and management) that tolerate disturbances and/or adapt to changes in ways that continue to provide ecosystem services and support human well-being is key to achieve landscape sustainability.

Hierarchy theory and cross-scale interactions are also central to LSS. Landscapes are mosaics of landscape elements in which people live and work, and through which the processes from local to regional and global scales are biophysically, socially, and economically linked. From this perspective, LSS is well suited in place-based research for achieving sustainability that can link local actions to regional constraints and the changing global context. Such emphases on the interactions and feedbacks between landscape-level changes, and their hierarchical linkages to both finer and broader scales are rooted in the hierarchy theory (O'Neill 1986), and are fundamental lens to take in studying LSS. This is especially true given that contemporary anthropogenic forcing is transforming the scales of social-ecological processes, resulting in interactions at novel and possibly unpredictable space–time combinations (Qiu et al. 2018a, b; Rose et al. 2017). Hence, despite place-based focus for many LSS studies, it is vital to explicitly address cross-scale interactions that encompass both spatial and temporal scales, and effects from distant systems (i.e., teleconnections) to better understand drivers and mechanisms of the dynamics between ecosystem services and human well-being in changing landscapes.

Methodological innovation for research

Thanks to ever-evolving spatial science methods in remote sensing, GIScience, and spatio-temporal analytics (Jenerette and Potere 2010; Schneider et al. 2010; Buyantuyev and Wu 2012), we now enjoy much improved capabilities to analyze the spatiotemporal patterns of landscape and its dynamics at multiple scales. More recently, scientists have been using powerful quantitative methods, such as Bayesian hierarchical models, machine learning, and numerical simulations, to explore and interpret important patterns in complex, multi-scale datasets to answer critical questions on landscape sustainability (Levy et al. 2014). The use of computational tools and technology, particularly their connection to scientific data, is increasingly important to answer fundamental questions on how to achieve sustainability goals across different landscapes.

Modeling is an important approach to investigate landscape sustainability and integrate the social and environmental components of coupled systems. Among various models, agent-based models (ABMs) and system dynamics models (SDMs) are gaining popularity, as they contribute to improving our understanding of complex system dynamics and shed light on landscape sustainability-related issues (e.g., rangeland management, water quality, air quality). ABMs, including cellular automata-based models, provide a disaggregated view, as they aim to incorporate the effect of human decision-making (along with its drivers) on the environment in a mechanistic and spatially explicit way, while considering social interaction and adaptation (Schlüter et al. 2019). ABMs are capable of modeling individual entities and their interactions, incorporating overarching influences on decision-making, and dynamically integrating social and environmental processes (Brown et al. 2005). ABMs also complement empirical research, which is generally limited in dealing with multiple dimensions and spatial scales due to logistic reasons. In addition, ABMs can capture the emergence of system characteristics based on individual interactions and feedbacks across different levels of organization (Egli et al. 2018). In particular, spatially-explicit ABMs (Schouten et al. 2013) have been emerging as a powerful approach to investigate LSS research questions.

In contrast, SDMs provide an aggregated view to examine emergent behaviors resulting from variable interactions in different domains of complex systems. While initially developed for application in industrial manufacturing, SDMs are widely applied to model landscape dynamics. In particular, SDMs can be used to synthesize different data types to investigate social-ecological systems where socioeconomic and environmental changes interact with each other to influence human decision-making in land use and natural resource management (Rasmussen et al. 2012). The simulated results on the trajectories of key variables over time, as well as their interaction patterns, shed light on major system characteristics (Allington et al. 2018). However, current SDMs are generally limited in its spatial capacity (He et al. 2005), and spatializing (or pixelizing) SDMs presents as an important topic for future research that will contribute to LSS.

Scenario-based approach is another popular method for anticipating the future given increasing complexity and uncertainty. Its recent applications span across natural resource management, land use planning, environmental conservation, and landscape sustainability. In these contexts, results simulated under different scenarios allow researchers to explore future ecosystem services (Bohensky et al. 2006), and examine climate change adaptation at different spatial scales (Ernst and van Riemsdijk 2013; Liao et al. 2016). In addition, adopting the scenario-based approach in the research process can facilitate participation of diverse stakeholders from different disciplines and social backgrounds to think and collaborate with each other to address a question of mutual interest (Allington et al. 2018). Scenario-based approach can be further integrated with simulation models and other quantitative tools to enrich its quantitative and spatial capacities.

Recent advancement in machine learning has expanded data-driven research on landscape sustainability, allowing artificial intelligence to infer system behaviors and outcomes by computing and exploring variables correlations. Compared to general linear models, machine-learning algorithms such as RandomForests, MaxEnt, and TreeNet are especially helpful to answer key landscape sustainability questions with regards to species distribution (Drew et al. 2010), conservation (Kampichler et al. 2010), and ecosystem services (Willcock et al. 2018) that often have emergent characteristics. In addition, machine learning can process a large number of variables and their interactions to identify major signals in the dataset (Cutler et al. 2007). As such, machine learning modeling techniques can decrypt complex non-linear relationships among variables that drive landscape processes and dynamics. While capable of incorporating multiple dimensions of landscape sustainability and their social-ecological determinants simultaneously, it is worth noting that the performance of machine learning algorithms largely depends on model parameters, structure, and settings (Zhang and Wallace 2015). In certain cases, the identified relationships may not be causal, and it can be an overstretch to extrapolate such relationships across space or time (Mullainathan and Spiess 2017).

Enhanced design for sustainability

Landscape design is crucial for extending the impact of LSS in the real world (Nassauer and Opdam 2008). Design, which refers to as any intentional configuration of landscape compositions for providing ecosystem services and meeting societal needs, provides a platform for scientists and stakeholders to apply scientific knowledge to support decision-making on landscape change. Landscape design thus forms the basis for understanding the process and pattern of interactions, and offers evidence to support adaptive management. For LSS to generate socially relevant knowledge and impact, it is necessary to sufficiently consider human needs, behaviors, and activities throughout the landscape (Opdam et al. 2013). This means that LSS must engage social sciences and seek input from different stakeholders and practitioners, and apply reflexive and iterative approaches throughout the design process (Foo et al. 2018). Meanwhile, scientific tools and design objectives should be co-developed and adapted with local stakeholders and practitioners to ensure relevance to local contexts, values, and interests.

Implementing landscape designs for sustainable outcomes requires clear communication of socioeconomic and environmental opportunities and concerns across different individuals and social groups (Dale et al. 2016). Therefore, it is necessary to reach a consensus by professionals and stakeholders that simultaneously considers future landscape functions, social value and justice, and the implications of higher-level plans and policies. Strategies to engage stakeholders such as mediation and joint fact-finding can be helpful for reaching agreements. In each scenario and stage of design, multiple alternatives should be created and assessed iteratively until a consensus is achieved. Instead of offering predetermined solutions that can be incompatible for implementation in a specific context, a design approach that fosters collective exploration before accepting any plans can better facilitate knowledge co-production and strengthen sense of ownership and responsibility (Berthet et al. 2019).

In addition to landscape design, geo-design is also gaining popularity for promoting sustainability outcomes. Geo-design, which represents a vision for using geographic knowledge in design, is a planning method that integrates the creation of design proposals and simulated socioeconomic and environmental outcomes that are informed by digital technology, system characteristics, geographic data (Steinitz 2012). Therefore, geo-design is a process that is usually supported by geospatial science and technology. Geo-design is also an interdisciplinary collaboration with interactions among design professionals, geographically-oriented scientists, and local residents (Slotterback et al. 2016). The ever-evolving computation capacity and geospatial tools for scenario generation and evaluation provide transformative opportunities for advancing the geo-design process.

In particular, combining design proposal creation and spatial analysis can lead to a revival of optimization in the planning process, which systematically searches throughout the space under different design considerations (Eikelboom et al. 2015). If properly integrated with LSS perspectives and approaches, geo-design can greatly contribute to promoting the science and practice of landscape sustainability (Huang et al. 2019; Wu 2019).

Application of LSS across landscapes

In this section, we discuss the applications of LSS across landscapes in the pursuit of multiple SDGs including Zero Hunger, Climate Action, and Life on Land. Specifically, we focus on food production, which is arguably one of the most critical challenges for human society in the 21st century to feed 9 billion population by 2050, reduce greenhouse gas emission, and halt landscape degradation and ecosystem service loss (Rockström et al. 2017). To address this challenge, many scholars advocate sustainable intensification for boosting crop productivity while minimizing environmental spillovers and maintaining fundamental ecosystem services (Tilman et al. 2011; Liao and Brown 2018). Various evidence suggests substantial yield gaps in many parts of the world, especially on the croplands throughout sub-Saharan Africa. On such agricultural landscape, strategies such as soil fertility enhancement, water management improvement, and technology innovation and transfer can be adopted to close the yield gap (Mueller et al. 2012). It is estimated that by 2050, moderate intensification at the global level can not only boost crop yield, but also cut cropland expansion by 80% and reduce greenhouse gas emission by 67% (Tilman et al. 2011).

In addition to intensification on existing agricultural landscape, the practice of urban agriculture can play a crucial role in reducing urban poverty and food insecurity while providing tremendous ecosystem services (Zezza and Tasciotti 2010). If urban agriculture is scaled to the global level, it can potentially produce 100–180 million tonnes of food, save 14–15 billion kilowatt hours of energy, sequestrate 100,000–170,000 tonnes of nitrogen, and avoid 45–57 billion cubic meters of storm water runoff annually (Clinton et al. 2018). However, further place-based research focused on urban areas in low-income countries where cities are characterized by high population density and poverty rates is required to assess the spectrum of potential benefits or tradeoffs associated with urban agriculture (Badami and Ramankutty 2015).

Besides meeting the growing food demand, it is also necessary to maintain fundamental ecosystem services and reduce biodiversity loss on the natural landscape. Land sparing, which is a land zoning strategy to spatially decouple food production and environmental conservation, has been commonly adopted by many national governments (Mertz and Mertens 2017). Simulated results suggest that improved land zoning can deliver greater environmental benefits and boost crop yields in both developing and developed country contexts (Law et al. 2015; Lamb et al. 2016). Various empirical evidence also supports the effectiveness of land sparing, especially when enforced in conjunction with other strategies such as technological innovation, agricultural extension, and payment for ecosystem services. For instance, the Costa Rican government promoted export-oriented agriculture by developing pineapple and banana plantations on existing ranches, and zoned conservation areas to protect its forest. Such strategies substantially increased agricultural productivity, and reduced forest clearance rate by 50% within the conservation zones (Fagan et al. 2013).

In contrast to land sparing where production and conservation is spatially decoupled, land sharing, which emphasizes spatial co-existence of high yields and high biodiversity on the agro-ecological landscape, is also gaining popularity (Perfecto and Vandermeer 2010). Through ecological intensification (i.e. adding tree cover or pollinators to the agricultural system), crop yield can be improved with mitigated anthropogenic inputs and enhanced ecosystem services (Toledo-Hernández et al. 2017). For example, with shade tree cover, cacao plantations in Indonesia not only demonstrate high yield, but also maintain higher biodiversity and deliver greater benefits in terms of carbon sequestration and storage (Rajab et al. 2016). However, the practice of ecological intensification cannot be overgeneralized, because its success rests on context-specific knowledge. Therefore, further research is needed to better understand how various organisms and community compositions provide different ecosystem services, and how to manage the new elements in the agro-ecological systems to avoid any potential damage (Rasmussen et al. 2017).

Applying LSS to the innovative landscape design across different landscapes has huge potential to contributing to food security, greenhouse gas emission reduction, and environmental conservation (Berthet et al. 2019). In this regard, knowledge on the functioning of agricultural-urban-natural landscapes sheds light on the scope for design, the stakeholders to engage, the variables to monitor, and the management practices to adopt. Promoting the application of LSS to innovative landscape design will benefit from infrastructures and institutions that facilitate the interactions between scientific research, food production, and environmental conservation. By facilitating collaborations and synergies among scientists, design professionals, and local stakeholders, these infrastructures and institutions can foster the application of cutting-edge LSS to the design of sustainable landscapes, and contribute to developing adaptive governance and ensuring long-term sustainability.

Conclusion

In this editorial, we provide a synthetic discussion of the theoretical foundation of LSS, the innovations in research methods and design, and its applications in the pursuit of multiple SDGs across different landscapes. We first argue that it is necessary to apply interdisciplinary research frameworks such as LSS and other closely related theories and concepts for designing, conserving, and managing our landscapes to sustainably provide ecosystem services and deliver societal needs now and into the future. Second, future research on landscape sustainability may take advantage of the methodological innovations such as SDMs, ABMs, scenario-based simulation, and machine learning, which will enable landscape sustainability scientists to investigate landscape dynamics and assess determinants of sustainability outcomes at an unprecedented level. Third, landscape design and geo-design, as major approaches to promote the real-world impact of LSS, will allow both researchers and practitioners to harness both theoretical and methodological innovations in LSS to configure landscape compositions for achieving multiple sustainability goals. Fourth, by synthesizing the application of LSS across agricultural, urban, and natural landscapes, we highlight that although landscape sustainability science as a framework can be used in either rural or urban settings, at its core is the emphasis on integration across different landscapes at a broader spatial context. The strong sustainability perspective suggests that long-term regional sustainability can only be achieved by integrating context-based sustainability in urban, agricultural, and natural landscapes so as to minimize the regional ecological footprint.

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