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PERSPECTIVE

Landscape sustainability and the landscape ecology of institutions

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Abstract
Context Landscape sustainability emerges from interactions between linked human and natural systems. Many of these interactions are mediated by institutions (e.g., rules, laws, customs, traditions), most of which are themselves spatially defined entities that both generate and respond to spatial variation in the landscape. However, the spatial dynamics of the interplay between institutions and landscape heterogeneity are poorly understood.
Objective To define the landscape ecology of institutions as an emerging research field, providing a summary of key themes and frontiers.
Methods We draw on existing theory in both landscape ecology and institutional analysis to explore the interface between landscape ecology and institutions in social-ecological systems.
Results Three central themes in understanding landscape sustainability through an institutional lens include the role of landscape heterogeneity as a driver of institutions; the spatial properties of institutions as influences on ecological and socioeconomic processes; and the relationships between institutions and landscape resilience. Emerging frontiers for further research include understanding the roles of top-down vs bottom up processes (design vs. emergence); understanding landscapes as institutional filters; the role of landscapes in institutional development and change; and co-evolutionary dynamics between landscapes and institutions. We discuss each of these points in detail.
Conclusions Spatially mediated feedbacks between landscape structure and institutions are poorly understood and critical for landscape sustainability. Further research in this area will depend heavily on generating data sets that describe the spatial properties of institutions and allow them to be analysed as landscape features.

Keywords Heterogeneity · Spatial resilience · Governance · Management emergence · Landscape change · Social-ecological system

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Introduction

Although social, economic, and ecological systems each have dynamics of their own, they are connected by a set of dependencies and feedbacks. Landscape sustainability refers to the "capacity of a landscape to consistently provide long-term, landscape-specific ecosystem services essential for maintaining and improving human well-being" (Wu 2013). Landscape sustainability is an anthropocentric concept; it emerges from spatially and temporally structured interactions between people and ecosystems (Matthews and Selman 2006; Wu 2013). In linked social-ecological systems (SESs), groups of people collectively regulate their environmental impacts and respond to environmental change via institutions, which are broadly defined as the formal and informal laws, rules, norms, traditions and customs that govern the interactions of human groups with their environment (McGinnis 2011).

Institutions are recognised as influences on land use by people (e.g., by imposing restrictions on movement, access, and extractive activities), and on resulting landscape change (Bhattarai and Hammig 2001; Rudel 2007; Chhatre and Agrawal 2008; Cox et al. 2010; Baggio et al. 2016), but they are often analysed as independent components of landscapes that have been designed by humans to achieve certain ends. Most social-ecological analyses of institutions have assumed that institutions cause patterns in ecosystems, rather than vice-versa. For example, Hardin's (1968) ideas on the tragedy of the commons are rooted in an outdated view of ecosystems, which implicitly assumes that human communities develop institutions to manage at-equilibrium resources (e.g., a grassland, a forest, or a wetland) and that ecological change away from equilibrium is due to human influences. Although there are some excellent analyses of institutional responses to ecological change (e.g., Bingeman et al. 2004, Berkes et al. 2008, Perry et al. 2011), the dominant focus of institutional analysis of SESs has been on understanding how institutions regulate the impacts of people on ecosystems.

In understanding the geography of SESs, a view of existing institutions (e.g., current patterns of land ownership) as structuring forces that act on ecosystems has led implicitly to the assumption that institutions organize spatial activity while themselves being largely independent of the same geographic relationships that define and structure ecosystems. Thus, for example, the spatial patterns in ecosystems that result from institutions are widely recognized and well analysed (e.g., changes or differences in deforestation patterns under different regulations) but the feedbacks from these patterns back to institutions (and especially, the creation and modification of institutions) are seldom explicitly analysed in studies of landscape ecology and land cover change and hence are poorly understood. While it seems obvious that a feedback from a management outcome to a subsequent management action should occur, the institutional contexts for such feedbacks are often un-documented and landscape ecology lacks theoretical frameworks with which to describe and interpret them, despite their interest to other research fields (Fairhead and Leach 1996; Scott 1998). Even the 'conservation evidence' literature, with its focus on empirically determining what works in conservation, does not currently include detailed descriptions of relevant policies and the broader institutional settings in which they occur (Adams and Sandbrook 2013). Similarly, relatively few studies in ecology have explicitly considered the constraints that ecosystem heterogeneity might impose on institutional design.

Like ecosystems, institutions can be viewed as spatially explicit, co-evolving landscape elements with emergent properties (Rammel et al. 2007). Institutions can also be classified into distinct types (e.g., public or private ownership of resources; informal or formal) that have shared elements (e.g., restrictions on access or use that occur across multiple localities), boundaries (e.g., national and municipal jurisdictions), and geographic connections (e.g., spatially located management agencies and policies that create commonalities in the management of different habitat patches across a heterogeneous landscape). Even when institutions are created at very broad spatial scales, as in the case of as national constitutions or global conventions, they may have higher relevance, effectiveness, or costs in some locations than in others (Swanson 2001).

If we wish to understand landscape sustainability, it is important that we develop a spatial understanding of institutions and their dynamics. Although institutions are developed through social processes, they are heavily influenced by ecological and geological landscape-level, pattern-process dynamics. Many human institutions are tightly connected to specific landscape

features – e.g., patches of forest, sacred groves, lakes, or mountains (Tengö et al. 2007). Boundaries between jurisdictions are often defined by geographic features such as rivers, mountains, or oceans. Human evolution, societal development, and settlement patterns are both driven and constrained by geography (e.g., Schnaiberg et al. 2002); it is only in very recent times that we have been able to partially overcome geographical constraints through modern transport and communications technologies. The feedbacks between people and landscapes have been moderated in space by institutions, which have played a key role in what Ellis (2015) terms 'niche construction' (i.e., the modification of natural environments to suit our own needs and institutions).

Recognition that most institutions are spatial entities suggests a natural relationship between institutional analysis, sustainability, and landscape ecology. For example, there is already a strong existing connection between these disciplines in the context of research on protected areas. Protected areas are an institution that is created by people, often with the explicit goal of either reducing the impact of broad-scale biophysical changes on biodiversity or ensuring the continued provision of a desired ecosystem service (Cumming et al. 2015). Most research on protected areas has focused on their relevance for biophysical processes (e.g., water provisioning, species dispersal, maintenance of threatened populations of animals and plants) rather than on understanding how and why their biophysical and socioeconomic environments have led to their creation. Analyses of protected area creation have generally been undertaken using a historical, political ecology, or conservation planning lens, although landscape ecology approaches have been used, for example, to show that statutory protected areas are typically situated at higher elevations and in locations that are more distant from human settlement than expected by chance; and that analyses of their local effects are scale-dependent (Joppa and Pfaff 2009; Ament and Cumming 2016).

Consideration of the close synergies between landscape ecology and institutional and political geography suggests at least three relatively unexplored areas of landscape sustainability research that have strong relevance for quantitative analyses of resilience, ecosystem services, and biodiversity conservation. These include (1) landscape heterogeneity as a driver of institutions; (2) spatial properties of institutions as influences on ecological and socioeconomic processes; and (3) institutions and landscape resilience. We discuss these three emerging research areas in more detail below and then consider some of the overarching questions and frontiers for research on institutions and landscape sustainability. Through this discussion, the relevance of the spatial analysis of institutions as a currently-missing element of landscape sustainability science becomes increasingly obvious.

Unifying themes linking landscapes and institutions

Landscape heterogeneity influences institutions

Landscape heterogeneity, incorporating spatial variation in elements of both the biophysical and socioeconomic system, exerts a considerable influence on the nature and function of institutions (Fig. 1). We lack a solid understanding of how landscape-level biophysical processes act to influence the creation or emergence of institutions, and few studies have quantified these relationships. However, several general principles and hypotheses for further testing can be proposed from previous research and existing examples.

Process heterogeneity

Spatial and temporal variability in biophysical processes play a critical role in structuring human interactions with the environment and as influences on the types of institutional arrangements that groups may adopt for addressing inherent social dilemmas that arise from the use of common-pool resources. Indeed, a significant fraction of institutional arrangements have arisen to support efforts to either reduce ecosystem variability (e.g., irrigation, stocking), cope with it (e.g., food storage), or capitalise on it (e.g., the harvest of spawning salmon). The spatiotemporal dynamics of ecosystems therefore influence institutional design and performance by affecting the information that groups possess concerning resource conditions and dynamics, their incentives to invest in the management of resources, and the relative efficiency and effectiveness of alternative institutions. Much as landscapes influence the relative distribution of different species and phenotypes, they also have a

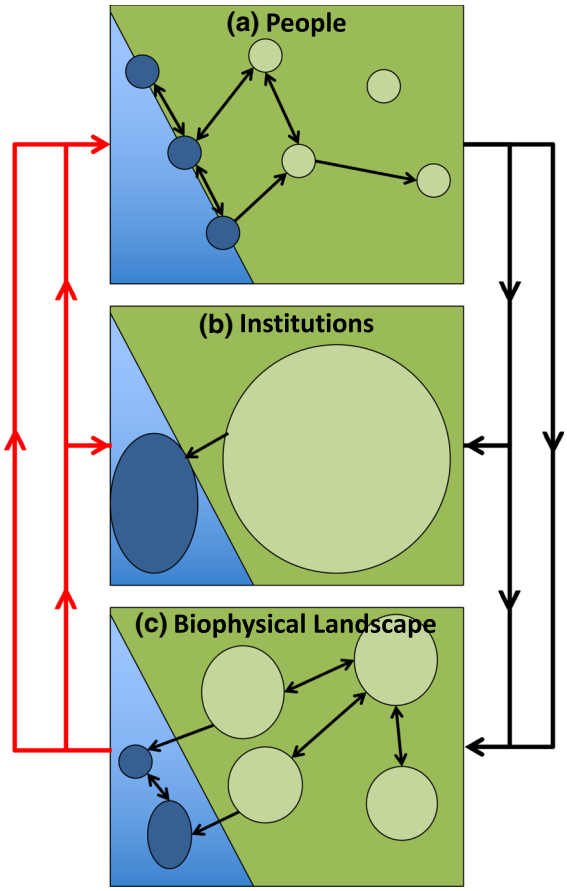

Fig. 1 Interactions of landscape pattern, human communities, and institutions. This figure shows a stylised coastal landscape in which settlement patterns of people have been driven by proximity to two coastal resources: fish, and fertile alluvial soils. **a** Landscape structure creates linear settlement patterns among fishers (blue nodes) and more dispersed patterns among farmers (green nodes). These in turn influence socioeconomic interactions (black links between nodes). **b** Resource management institutions have a geographic structure due to their different foci (land management, green node; sea management, blue node), but are connected in space (black link) via the need to manage sediment and pollutant runoff that impacts reef condition. **c** The biophysical landscape supports agricultural fields (green nodes) and reefs (blue nodes) that are connected by nutrient flows and the movements of organisms, such as pollinators and predators. Interactions between people, institutions, and landscape pattern are shown by black arrows (direct impacts of people on institutions and landscapes; indirect impacts via institutions) and red arrows (direct impacts of landscapes on people and institutions; indirect impacts of landscape structure on people)

systematic effect on institutions. Landscape type and structure can be viewed as a coarse filter that makes certain kinds of institution untenable or irrelevant. For example, different kinds of farming practice – and different biophysical limits and ecological responses to cultivation – apply in highland vs lowland systems, necessitating different kinds of institutions for managing them (e.g., Greiner et al. 2013). Similarly, institutions that regulate use of stocks (e.g., timber, herbivore populations) tend to have different properties from those that regulate flows (e.g., water extraction from rivers, nutrient cycles).

Resource mobility, heterogeneity, and infrastructure

Landscape heterogeneity, particularly when it is systematically arranged in a gradient, is a form of asymmetry that can drive the movements of substances or agents (Cumming et al. 2008). For example, water flows downhill; many animals move between resource-rich patches; and people often move to cities seeking economic opportunities. Ostrom's (1990) design principles for community-based natural resource management highlight convergent patterns in the high-level features of institutions that groups adopt to effectively address common-pool resource problems. These include features that continue to enjoy robust empirical support across diverse cases (Cox et al. 2010)—e.g., the participation of resource users in decision-making, clear social boundaries, accountable monitors, and graduated sanctioning. Furthermore, larger social-ecological systems with mobile resources (e.g., water, animals) that move across the boundaries of multiple communities in response to landscape heterogeneity often adopt nested governance, in which tasks such as monitoring and sanctioning are handled by individual communities while higher-order community organizations ensure coordination of rules and activities across multiple communities (Ostrom 1990; Wyborn and Bixler 2013; Raakjaer et al. 2014).

Recent research has also shown that the relative importance of individual design principles varies systematically across cases, depending upon the relative mobility of resources and need for developing and maintaining infrastructure such as irrigation canals. For example, while monitoring is critically important in systems that require considerable investment in hard infrastructure (e.g., fences, impoundments, irrigation channels), clear social boundaries are more important in systems where resources, such as aggregations of animals, are mobile and respond to

temporal variation in spatial heterogeneity (Baggio et al. 2016). Although clear boundaries are generally conducive to collective action and sustainable environmental governance by internalizing the costs and benefits of resource use (Ostrom 1990; Cox et al. 2010), governance systems with fuzzy boundaries often emerge in the context of resources with high levels of spatiotemporal variability, such as rangelands that experience high spatial and temporal variance in rainfall, herbivory, and disturbance regimes (Banks 2003; McAllister et al. 2006). Fuzzy boundaries may serve a range of potentially important functions in such contexts, including providing economies of scale in exclusion and herd supervision and mitigating risks against variability in resource conditions (Scoones 1995; Banks 2003).

Resource mobility has also been implicated as a core influence on the types of rules that groups adopt to govern the appropriation of resources. Groups exploiting immobile resources such as trees or groundwater basins tend to adopt quantity rules that place numerical restrictions on the amount of a resource that might be harvested; by contrast, groups exploiting mobile resources tend to employ access, timing and location rules that define where, when, by whom, and for how long harvests may occur (Schlager et al. 1994). The effects of mobility on institutions, however, appear to be mediated by the availability of storage, which facilitates the use of quantity rules (Schlager et al. 1994).

Generic spatial properties

Given that most institutions are geographic entities (i.e., they are physically located in space), we would predict that they exhibit typical properties of spatially structured systems. These include, among others, (a) alignment with natural boundaries (e.g., rivers, mountain ranges); (b) spatial dependence or core-periphery effects on effectiveness (e.g., strength of implementation or enforcement changes between the middle and the edges of the area in question; kinds of institutions vary with distance to human settlement); (c) relevance of spatial configuration as well as total area (e.g., potential for fragmentation to weaken or modify existing institutions); and (d) a potential for contagion (e.g., institutions being copied or transferred successfully between ecologically similar patches in close proximity).

The value of aligning institutions with natural boundaries is demonstrated by water management institutions, which serve to regulate shared flows of water that move from high to low parts of a landscape. The widespread push towards the formation of catchment management districts, for example, shows the role of ecosystems in forcing institutions and political processes to align to natural boundaries and ecosystem processes (Nilsson and Malm-Renöfält 2008; Warner et al. 2008). A converse example is that of many political boundaries in Africa, which were imposed by European powers using natural features that in many cases had no direct relationship to the pre-colonial geographic structure of different tribal holdings and kingdoms. Ongoing separation of different ethnic and religious groups into different nation states, and forcing of different groups into the same states, remains a major underlying driver of conflict (Englebert et al. 2002).

Spatial variance in institutional effectiveness or success is common in many systems, as evidenced by edge effects and core-periphery effects. For example, system boundaries may act as entry points for rule breakers (e.g., poachers in protected areas); inaccessible areas may become ungovernable (e.g., illegal, unregulated and unreported fishing on the high seas; Dunn et al. (2018)); and particular kinds of institution, such as protected areas, occur at non-random locations along socioeconomic and biophysical gradients. The 'high and far' placement of protected areas (Joppa and Pfaff 2009) is usually explained as the reluctance of societies to compromise their use of easily accessible resources, but it can equally well be viewed as an emergent spatial pattern pertaining to a particular kind of institution.

The spatial configurations and areas of institutions also interact strongly with human political and economic concerns. People are highly sensitive to perceived inequalities across groups and rapid change, and thus are unlikely to willingly accept rules and regulations that alter recent patterns of use or are different from those of their neighbours (Sick 2008). For example, success in conservation may be less likely if a conservation area that imposes local restrictions on resource use or displaces local people is adjacent to areas used by a community for provisioning services (e.g., firewood, hunting, non-timber forest products) (Coad et al. 2008).

Finally, institutions can spread or be lost through spatially contagious processes (Mills et al. 2019). Successful attempts to introduce new farming techniques often focus on people who can serve as role models and whose fields are visible to others in the community. Farmers are more likely to notice how their neighbours are managing their land than those far away, and to collaborate with them to manage scarce resources (Bala and Goyal 1998); and successful institutions for managing fisheries can spread around coastlines (Makino and Matsuda 2005). Zimbabwe's ground-breaking CAMPFIRE (Communal Areas Management Program For Indigenous REsources) program, for example, became a regional role model for community-based conservation (Biggs et al. 2019). Similarly, in-migration can result in the breakdown of traditional institutions in the receiving community, such as customs and taboos, that served a role in regulating ecosystems (Lingard et al. 2003).

Spatial properties of institutions influence spatial dynamics of ecological and socioeconomic processes

Once people have developed and implemented institutions to govern the use of a particular area and resource, institutions undergo a lifecycle of further implementation, testing, modification, and adaptation (Armitage et al. 2011). They may be strengthened if successful, or dropped entirely if unsuccessful. Their success or failure in turn depends heavily on dynamic changes in biophysical systems; in the dialogue between ecosystems and people, institutions can both alter outcomes and become victims of unexpected change (Galaz et al. 2011).

Institutions can channel, create, and drive change in ecological and socioeconomic processes. There is less research on how these changes in turn feed back to drive institutional change, leading to social-ecological feedbacks that are moderated by spatial patterns in ecosystems. One critical area in which institutions have a spatial influence on ecosystems is through their effect on the dispersal of organisms. The Convention on Migratory Species (CMS) is probably the best-known international example of deliberate management of ecological dispersal (Hykle 2002; Runge et al. 2015), and there is an extensive literature on the creation and value of wildlife corridors (Gilbert-Norton et al. 2010); but a range of institutions that were often not explicitly developed for the purpose of managing dispersal (e.g., protected areas, sacred groves, laws preventing riparian clearing, urban green spaces) can facilitate the movements of organisms through inhabited landscapes (e.g., Bodin et al. 2006, Sekercioglu 2009, Suri et al. 2017). Institutions that facilitate dispersal can affect the rate of recolonization of natural habitat; the kinds of ecological interaction that occur (e.g., competition, predation); and ultimately, the ability of the ecological components of a landscape to recover from perturbations (Bengtsson et al. 2003).

Conversely, institutions that restrict the movement of species (particularly, by people) can be vital in limiting the spread of invasive and exotic species, as well as pathogens and parasites (Fèvre et al. 2006). Introductions of invasive or pathogenic species can also lead to the creation of new institutions and accompanying infrastructure (Bax et al. 2001); the spread of Asian Carp throughout much of the Mississippi River Basin, and concerns about their potential spread to the Great Lakes ecosystem, provides an illustrative example (Chick and Pegg 2001; Fowler et al. 2007). These processes and their outcomes almost always have a strong spatial footprint, as evidenced by the existence of game fences, impoundments, customs controls, and other barriers to movement.

Spatial patterns in institutions also have indirect effects on ecosystems through their effects on information sharing. As management practices are developed, information is shared through human social networks (black lines in Fig. 1a), leading in turn to the spread of successful approaches and their formalisation in rules and laws. For protected areas, for example, management-related information and resources are shared more closely between adjacent or nearby properties and individuals, where trust is likely to be higher and problems more likely to be similar (Maciejewski and Cumming 2015). The influence of the spatial structure of different land tenure types on the spatial dynamics of how rules are developed and spread are, however, poorly understood as influences on landscape sustainability. For example, while we would predict that landscapes with highly heterogeneous patterns of rules should be harder to achieve coordinated management within (e.g., implementing controlled burns to regulate wildfire may be harder with a mix of private and public lands),

feedbacks from landscape heterogeneity to the creation and evolution of rules are harder to predict.

Finally, so-called 'higher order' or emergent properties of the spatial patterns of institutions—for example, drawing parallels to standard concepts in ecology, measures of institutional diversity, institutional turnover and replacement rates in space and time (e.g., whether even or clumped around boundaries), and meta-communities of institutions—represent an area of research in which little activity has occurred (Lansing and Kremer 1993). One recent example is an analysis of spatial patterns in the number and kinds of permissions issued by the Great Barrier Reef Marine Park Authority from 2007 to 2017 (Fig. 2; Cumming and Dobbs 2019). This analysis found a strong influence of human geography on the spatial pattern of reef-related permit applications over the GBR seascape, suggesting ways in which spatially explicit analysis of institutions could be useful for projecting future management needs.

Institutions and landscape resilience

Institutions are clearly relevant for landscape sustainability and social-ecological resilience, given that they act to mediate interactions (in both directions) between people and ecosystems (Matthews and Selman 2006; Cumming 2011a). Achieving a rigorous understanding of landscape sustainability, the focus of this special feature, will require that we develop better ways of mapping and interrogating spatial patterns of institutions and the feedbacks that occur between institutions and ecosystems. There are two areas in this theme that are poorly understood and require more research.

First, approaches to conceptualising and quantifying scale (and particularly, the ways in which different institutions can fit together to create a sustainable portfolio) are still poorly developed. Although we have a general notion that institutional, management, and ecological scales must somehow align in order for

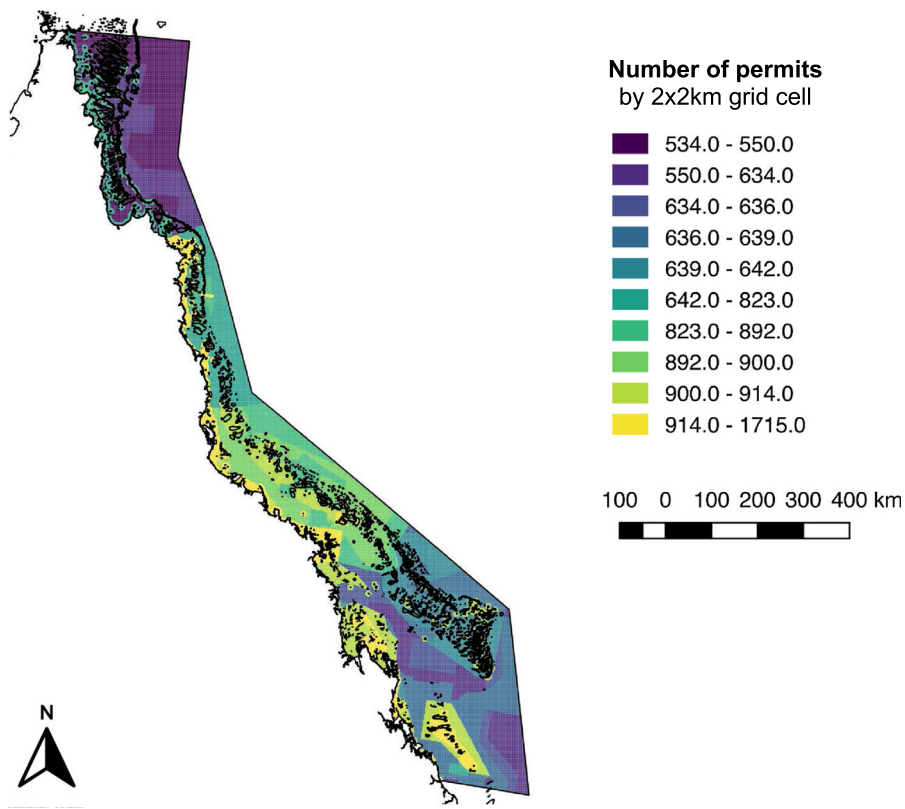

Fig. 2 Spatial patterns in numbers of permissions by 2 × 2 km grid cell for all permit types across the Great Barrier Reef Marine Park in Australia. The influences of both biophysical features (particularly, the coastline and adjacent coral reefs) and institutions (management zones and restrictions on particular kinds of activity in particular locations) is clearly visible

a system to be resilient (Cumming et al. 2006; Epstein et al. 2015), few studies have directly measured institutional and ecological scales and compared them. Thus, it remains unclear whether there is indeed some ideal alignment of institutions and ecosystems; and if so, whether achieving social-ecological fit means having institutional scales that correspond directly to ecological processes or whether some other kind of alignment might be more effective. Similarly, it is unclear how systemic properties such as resilience and resistance vary across scales, and whether they reside more strongly at a particular scale. Recent institutional research has used quantitative network analysis to explore the potential outcomes of different arrangements of interacting social nodes (people or organizations), but not in tandem with quantitative analyses of the relevance and the causes of ecological variance (Guerrero et al. 2013).

Second, the geographic area of an institution, the scale of governance from which it derives its mandate, and the power dynamics associated with that area are often ignored in landscape ecology and conservation. For example, Ramsar wetlands are declared under a global convention but may be relatively small in size; and national governments may not be strongly committed to enforcing global treaties unless they also align well with local priorities (e.g., Cumming et al. 2013, Hettiarachchi et al. 2015). We do not have enough data to propose a clear hypothesis about how differences in the spatial scales of the different levels of institutions governing a Ramsar wetland translate into effectiveness in biodiversity conservation or the resilience of the institution to external pressures (e.g., poor governance or management at an inappropriate scale as described by Cumming et al. (2013)). Before deciding what and how to measure, we need a better theory of institutions that allows us to link their structure to the outcomes they produce and thus to identify which spatial properties of an institution should be most relevant to its ability to achieve its goal while persisting (being resilient). Measuring these properties across many different systems and comparing them to on-the-ground outcomes may then provide some level of generality (e.g., Cinner et al. 2016). As this discussion suggests, any structure–function theory of institutions needs to consider space and spatial dynamics as potential influences that may influence outcomes, including institutional resilience, in social-ecological systems (Cumming 2011b).

Frontiers in landscape ecology and institutional theory

The preceding sections highlight several opportunities for advancing a co-evolutionary theory of institutional development and landscape change that is attentive to the spatial properties of both institutions and landscapes. We consider four emerging research areas to be of particular importance in this context. Some of these frontiers are already well recognised in institutional analysis, but they have not been integrated with landscape ecology perspectives on spatial pattern-process dynamics and hence are poorly incorporated into spatially explicit understandings of landscape sustainability. They include:

(1) Institutional design vs. emergence: do environmental governance institutions arise primarily from human agency and institutional design, or are they better viewed as emergent outcomes of spatially structured social-ecological processes? How can top-down and bottom-up approaches be successfully analysed and combined in understanding influences on institutional spatial patterns?
(2) Landscapes as a filter: what landscape attributes or characteristics determine the fitness of institutions for environmental governance? Do certain landscape patterns, for example, make some kinds of institution untenable?
(3) Spatially explicit institutional development and change: what spatially explicit processes underlie institutional development and change across social-ecological landscapes? Do certain kinds of landscape patterns facilitate or impede institutional development?
(4) Co-evolutionary dynamics: under what conditions do landscapes and institutions co-evolve towards greater sustainability, and can this process be facilitated or guided to enhance landscape sustainability?

We next discuss each area in more detail.

Spatially explicit institutional design vs. emergence

Any co-evolutionary theory of institutional development and change must confront longstanding questions in institutional theory concerning the role of

human agency in the design and development of institutions (Giddens 1984). Institutional theory is a diverse field of research encompassing a range of approaches, methods and assumptions (Mitchell 1988; Hall and Taylor 1996; Peters 2012); all of these approaches do, however, share the view that institutions give order to human interactions by providing a template for making decisions. Although institutional theory has made considerable progress in understanding the consequences of different institutional arrangements, important questions remain with respect to the conditions and processes by which institutions emerge and change and the relevance of spatial variation for these processes. Many rational choice institutionalists, for instance, argue that institutions emerge as equilibrium solutions to problems, and can change relatively swiftly with changes in the environment that alter the incentives, opportunities and constraints that actors face (Shepsle 2006). In contrast, many historical institutionalists argue that institutions themselves provide a deeper structure to institutional development and change that provide selective incentives and opportunities that favour the persistence of core institutional structures (North 1990; Pierson 2000). Empirical evidence suggests that different core institutional structures are dominant in different settings, with several examples of communities successfully transitioning from government-led to co-managed systems (Ebbin 2002; Dobson and Lynch 2003; Ayers and Kittinger 2014); while other decentralization initiatives have floundered as politicians, bureaucrats and local elites exploit opportunities to retain control over the use and management of natural resources (Blaikie 2006; Ribot et al. 2006). Both perspectives share a common view that the social, ecological and institutional features of landscapes play an important role in influencing the type of institutions that are used to address issues in landscape sustainability, and their relative effectiveness in addressing those issues.

Scale is a critical concern in thinking about both institutional design and institutional emergence. If institutions form or are created in response to environmental heterogeneity, then the characteristic scales of environmental heterogeneity should leave their imprint on the number and nature of institutions occurring in a given landscape. At the same time, socioeconomic processes and pressures on landscapes (e.g., urbanization, fisheries) often occur at particular scales, which may be more appropriate for developing institutional responses. Thus, the dominant scales of institutions are likely to reflect the dominant scales of social, ecological, economic, and social-ecological processes.

Landscapes as a filter for institutions

While previous generations of landscape ecologists and environmental planners tended to view environmental problems in terms of the natural and technical features that defined them, social-ecological perspectives highlight the need to attend equally to their social, economic and political dimensions (Brandon and Wells 1992; Ostrom 2009; Bennett et al. 2017). Several attempts to improve the fit between ecosystems and institutions, such as adjusting governance boundaries to match the distribution of a resource, have failed due to a lack of fit with the broader social and institutional context of heterogenous resource users (Moss 2003; Acheson 2006). As a result, there is a growing need to develop a better understanding of the role and relative importance of potential agents of selection within complex social-ecological landscapes.

The sheer number and diversity of potentially relevant social, ecological and institutional features of social-ecological landscapes presents an immense analytical challenge (Ostrom 2009). Nonetheless, scholars have been able to gain traction on such questions by examining the institutions that are used and their performance along socioeconomic and biophysical gradients. Leadership and social capital, for instance, may facilitate the emergence and effective functioning of community-based or collaborative environmental governance (Singleton and Taylor 1992; Pretty and Smith 2004; Van Laerhoven 2010; Gutierrez et al. 2011; Marín et al. 2012). Nested governance systems, meanwhile, frequently emerge to govern the use of resources distributed over larger spatial scales (Ostrom 1990; Wyborn and Bixler 2013); while spatiotemporal variability in resources often results in the adoption of governance systems with fuzzy, partially overlapping boundaries (Scoones 1995; McAllister et al. 2006). The next generation of research on institutions and landscape sustainability must, however, move beyond the analysis of individual features to examine how these features interact to jointly influence the structure of social-ecological landscapes and understand their implications for the

emergence and design of effective institutions. Early efforts to respond to this challenge have focused on developing systems for classifying and analyzing social-ecological landscapes based on the nature of the resource and related public infrastructure (Baggio et al. 2016), the levels at which components are aggregated and the nature of governance challenge(s) (Bodin et al. 2019) and building diagnostic trees (Young 2019). Similarly, others have highlighted the need to develop better, and often multiple, measures of core concepts such as leadership, social capital and success to develop a more nuanced understanding of social-ecological processes and outcomes (Coulthard et al. 2011; Evans et al. 2015).

Institutional development and change

The mechanisms by which institutional arrangements—including their boundaries and other spatial attributes—are developed, persist, and change within social-ecological landscapes are still poorly understood. This issue has been a subject of considerable theoretical debate in organizational theory, which seeks to explain the remarkable lack of diversity in organizational structures (i.e., rules that direct activities) and cultures within organizational fields. For some this lack of diversity reflects selective pressures (e.g., economic cost) acting via the nature of the task environment, and the relative efficiency or effectiveness of alternative organizational forms (Perrow 1967; Hannan and Freeman 1977). For instance, it has been suggested that the general absence of quantity rules for mobile resources stems from the costs associated with acquiring reliable information about the conditions of resources (Schlager et al. 1994). Others have countered this assertion by suggesting that institutional isomorphism is driven strongly by social and institutional factors that grant legitimacy to certain types of organizational structures through three key processes: coercive, mimetic and normative (DiMaggio and Powell 1983).

Laws and policies exert a coercive pressure on organizations, compelling them to adopt certain institutional arrangements to fulfill legally required functions, satisfy government mandates, and obtain funding support. These institutions often have strong spatial and cross-scale components that influence outcomes. Many international donors and national governments have, for example, leveraged their financial resources and legislative powers to compel communities and state officials to collaborate in the management of local resources (Dobson and Lynch 2003; Morrison 2007; Agrawal et al. 2008). The results of decentralization reforms have, however, varied widely across different social and ecological landscapes. In some contexts communities have responded favourably, investing time and resources in natural resource governance (Coleman and Fleischman 2012) and contributing towards more sustainable outcomes (Wright et al. 2016). However, in many cases decentralization has failed to achieve these objectives as state actors and local elites exploit opportunities to retain or enhance their control over the governance of resources (Blaikie 2006; Ribot et al. 2006; Béné et al. 2009).

Institutional isomorphism can also result from mimetic processes in which organizations are confronted by uncertainty, and elect to respond to this uncertainty by copying the institutional structures of similar organizations that are perceived to be successful (DiMaggio and Powell 1983). Success-biased transmission of institutional arrangements across social-ecological landscapes may result from a range of processes, including social ties across communities, information sharing through the media and networks and formal knowledge transfer activities. Many of these interactions are influenced by landscape structure. In fact, one recent study found that conservation initiatives tend to spread like a contagion within countries, with a slow build-up followed by a rapid rise and gradual attenuation within a population of potential adopters; and that adoption was generally supported by efforts to facilitate connections between early and potential adopters (Mills et al. 2019).

Normative models of institutional change are fairly similar to mimetic processes in that networks are often a critical conduit through which information about institutions spreads across organizations and social-ecological landscapes (DiMaggio and Powell 1983). They differ, however, in that transmission is guided by norms and taken-for-granted assumptions regarding the "appropriateness" of alternative institutional arrangements that develop through training and professional networks. For instance, the rise of participatory environmental governance has been accompanied by a similar growth in research and training in community-based environmental governance across diverse disciplines (van Laerhoven and Ostrom 2007)

and the adoption of participation as a general principle for sustainable environmental stewardship (Mangel et al. 1996; Reed 2008). Although debates exist about how functionalist, coercive, mimetic and normative models of institutional development and change influence the structure and function of institutions, there is empirical support for each model (Liang et al. 2007; Heugens and Lander 2009; Martínez-Ferrero and García-Sánchez 2017). However, despite their utility for understanding patterns in institutional development and change, there is a critical gap in understanding the landscape context in which each model might support the adoption or emergence of institutions that are more (or less) effective or efficient at addressing issues of landscape sustainability.

Co-evolutionary dynamics

The fourth and final set of questions for advancing a co-evolutionary theory of institutional development and landscape change centers on developing an understanding of how institutions and landscapes co-evolve to support landscape sustainability. Functionalist approaches to institutional change (i.e., where institutions succeed or die out depending on their success), for instance, appear well suited to achieving landscape sustainability in dynamic social-ecological landscapes. In theory, landscape change compels actors to organize and develop appropriate institutional responses that are better adjusted to current conditions. For example, the Paraíba do Sul river basin council in Brazil was able to effectively respond to a prolonged drought by shifting decision-making from a large deliberative council to a smaller technical working group to make time-sensitive decisions (Engle and Lemos 2010). However, in some cases groups may struggle to adequately respond to changes in social and ecological conditions due to high transaction costs (Marshall 2013), or fail to improve long-term sustainability as decision-makers elect to pursue other objectives that align with their own selective interests (Fazey et al. 2011; Müller et al. 2017). Furthermore, investments in public and private infrastructure and technology can create substantial barriers to institutional change and support the persistence of relatively inefficient and unsustainable institutions (Beddoe et al. 2009; Fouquet 2016).

Coercive, mimetic and normative pressures on institutional development and change are equally undirected as they tend to prescribe common institutional solutions across a vast and spatially heterogenous area. Historically, it is probable that many institutional arrangements emerged from long-term trial-and-error processes at a relatively local scale as communities experimented with institutional solutions to diverse social and environmental problems (Ostrom 1998). More recently, however, national governments and international organizations have used their knowledge, resources and coercive pressures to support first the nationalization and then the decentralization of natural resource governance (Johannes 1978, 2002; Conyers 1983). Although these efforts are often (but not always) well-intentioned and may correspond to the levels at which many of the drivers of ecosystem change operate (Nelson et al. 2006), they tend to neglect the spatially heterogenous nature of social-ecological landscapes (Acheson 2006). In fact, even success-biased transmission of institutions can be problematic if one or more of the critical ingredients that underlie their effectiveness, such as leadership, social capital, or particular landscape structures or resource distributions, are lacking in recipient communities or diminish over time. For example, institutions that are created under conditions of homogeneous resource abundance or low access to markets may be unsuited to dealing with conditions of heterogeneous resource abundance or easy access to markets (Cinner et al. 2016). Furthermore, national governments and international organizations may support the persistence of relatively ineffective and inefficient local institutions through exogenous flows of resources and erecting barriers to local institutional change, or undermine existing solutions (Morrison 2017).

Despite these concerns, institutional theory can still provide several potentially valuable insights to support the co-evolution of institutions and landscape sustainability. First, much as landscape ecology has come to appreciate the multi-level nature of biophysical systems (Cushman and McGarigal 2002; Cumming et al. 2015; McGarigal et al. 2016), institutional scholarship increasingly highlights the potential benefits of developing multi-level systems of environmental governance (Armitage 2007; Lockwood et al. 2009; Basurto 2013). Multi-level and multi-scale governance systems can serve a number of potentially important functions, including the provison of mechanisms to address external threats (Berkes 2006;

Cudney-Bueno and Basurto 2009), leveraging knowledge and resources across scale (Cash et al. 2006), and facilitating the coordination of institutions at relevant spatial scales while allowing for some flexibility to adjust or facilitate the emergence of institutions that fit local conditions (Bodin 2017).

Second, efforts to enhance the participation and influence of local resource users are likely to support the emergence of local institutions to effectively address cooperation and landscape sustainability problems. Resource users generally possess unique and potentially valuable local knowledge that might facilitate the development of rules that are particularly well suited to local conditions (Ebbin 2002; Chhatre and Agrawal 2009). For example, small-scale irrigation systems often rely upon a rotation system for the allocation of water, such that monitoring is produced as a byproduct of appropriation as irrigators approach the main canal to open and close the gates to their respective fields (Ostrom 1990). Local subsistence resource users with relatively secure rights to a resource are also likely to adopt lower discount rates and thus possess the strongest incentives to ensure the long-term sustainability of resource flows (Ostrom 2000). Participation in decision-making has also been consistently linked to higher levels of cooperation in groups facing social dilemmas (Ostrom et al. 1994; DeCaro et al. 2015; Epstein 2017), providing mechanisms to establish commitments, build trust and potentially "crowding-in" pro-social incentives that favour cooperation (Frey and Jegen 2001). There is, however, a need for further research to develop a better understanding of how spatial scales mediate how actors participate in landscape governance and its corresponding impacts on behavior and landscape sustainability.

Concluding comments

We have outlined several areas in which deeper consideration of the spatial dynamics and structure of institutions are likely to be important for landscape sustainability. If landscape structure drives the creation of institutions, and institutions in turn modify landscape structure by defining the kinds of activities that can occur in different locations, the interplay between biophysical systems and institutions can be viewed as a series of spatially-structured feedbacks that can in theory lead to a wide range of different social-ecological, pattern-process dynamics (Cumming and Peterson 2017).

Understanding these dynamics with any empirical rigour will depend on developing spatially explicit comparative empirical data sets and models. Detailed, spatially explicit data sets for institutions, such as the permit data used by Cumming & Dobbs (2019), appear to be unusual in institutional scholarship on social-ecological systems (see Poteete and Ostrom 2008). There must, however, be large numbers of such spatially explicit data sets that have been collected primarily for monitoring and enforcement purposes; accessing and sharing more of these dormant resources could provide an exciting entry point into understanding the landscape ecology of institutions.

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