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Perspective Essay

Forest landscapes as social-ecological systems and implications for management

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ABSTRACT

Many of the most pressing threats to forests result from complex interactions between multiple stressors and require management on large spatial and temporal scales. For this reason, many ecosystem managers have begun to recognize the need to consider the broader context of decisions, and how outcomes of past, present and future decisions in one location may interact with outcomes of such decisions in other locations nearby. The landscape has been put forth as an appropriate unit for such holistic approaches to management. However, as there are differing definitions of landscapes, it can be difficult to develop frameworks for management. Moreover, many definitions do not fully account for the many ways social and ecological conditions and processes interact within landscapes. Building on emerging theoretical and empirical literature, I offer a perspective on temperate forest landscapes as social-ecological systems: nested sets of coevolving social and natural subsystems connected through feedbacks, time lags, and cross-scale interactions. This interdisciplinary framing emphasizes the biogeophysical and socio-cultural influences on landscapes and the need to consider these influences – and the interactions among them – in management. I discuss challenges to managing forest landscapes as social-ecological systems that stem from mismatches in the temporal and spatial scales on which ecological and social systems typically function, as well as opportunities for policies, formal organizations, and governance networks.

1. Introduction

Many of the most pressing threats to forests today require management on large spatial and temporal scales. Wildfires, invasive species, and plant diseases, for example, do not observe administrative boundaries; rather, their behavior is a function of ecological patterns and processes across large areas. Moreover, land management practices influence ecological patterns and processes well into the future with impacts that often go unobserved for long periods of time. For these reasons, the forest management literature has begun to recognize the need to consider the broader context of decisions, and how the outcomes of present and future decisions in one location may interact with environmental conditions and processes, which are themselves outcomes of past decisions, and decisions made in other locations nearby (Filotas et al., 2014; Messier et al., 2015; Nocentini et al., 2017; Rist and Moen, 2013; Stephens et al., 2013). In other words, emerging paradigms of forest management emphasize the need to consider the many ways social and ecological conditions and processes (i.e., systems) interact to shape landscapes across space and time.

The landscape has been recognized as one of the most suitable spatial units for managing forests and other ecological systems (Brunckhorst, 2011; Forman, 1995; Forman and Godron, 1986; Phillips, 1998; Wu, 2012). Indeed, many of the social and ecological processes that affect trees and the forests they comprise occur on spatial and temporal scales typical of visible areas of land commonly referred to as landscapes. These processes unfold over geographic extents larger than the patch yet smaller than the region, and over time horizons on the order of decades and centuries (Fig. 1). However, as there are differing definitions of landscapes, it can be difficult to develop frameworks for landscape management (Antrop, 2006). On the one hand, landscapes have been defined on the basis of the ecological processes that shape them, that is, as diverse combinations of ecosystems at intermediate scales that affect each other across space and time within hierarchies of interdependent ecological processes (Nassauer, 1997; Wiens, 1999). Landscapes have also been defined on the basis of the social processes that shape them. In this view, landscapes, which have been modified by human activity, reflect cultural values and conventions and can therefore be viewed as social phenomena (Nassauer, 1995; Sauer, 1925). Some definitions integrate these two elements, social and ecological, describing landscapes as a nexus of nature and culture, encompassing environmental, economic, and social processes (Antrop, 1997; Brunckhorst et al., 2006; Jacobs, 1991; Nassauer, 2012; Pinto-Correia and Kristensen, 2013; Tress and Tress, 2001). More recently, a number of scholars (e.g., Angelstam et al., 2013; De Aranzabal et al., 2008;

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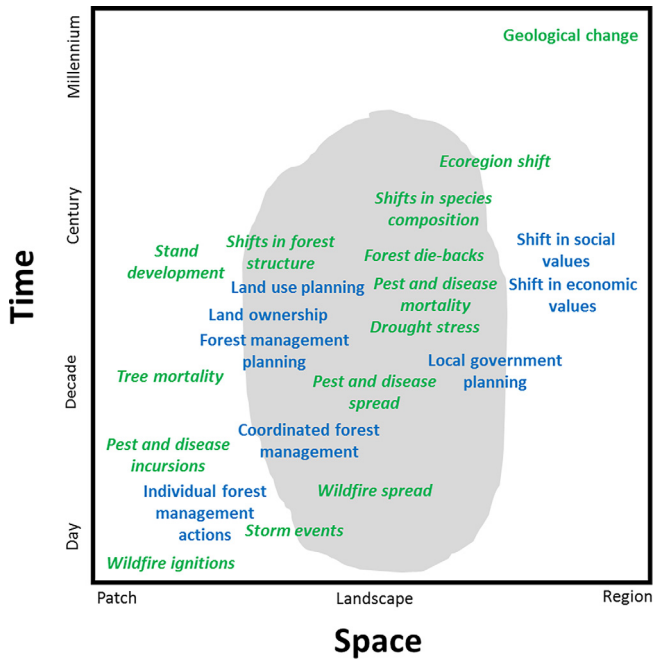

Fig. 1. Spatial and temporal scales of social processes (bold blue font) and ecological processes (italicized green font) that affect forests, many of which occur on the landscape scale (grey oval). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Gobster and Xiang, 2012; Matthews and Selman, 2006; Spies et al., 2014) have come to think of landscapes as spatial units in which many fundamental processes of social and ecological systems unfold, and thus have conceptualized landscapes as social-ecological systems (SESs) in and of themselves: interacting sets of interdependent bio-geophysical components and associated social actors (Liu, Dietz, Carpenter, Alberti, et al., 2007a; Ostrom, 2009).

Although all types of landscapes – terrestrial and marine – can be viewed through the lens of SESs, forest landscapes comprise a particularly intriguing type of SES because of their temporal and spatial dynamics. Trees can live for hundreds, sometimes thousands, of years, and many of the changes that affect them-disturbances such as wildfires and invasive plant, pest, and pathogen outbreaks, for example-are the result of former management practices and policies, as well as social and economic changes. Forest management actions can have unintended consequences that cause changes in distant locations at points far in the future (i.e., stages in forest succession), spanning decades, and in some cases, centuries. The process of coupled social-ecological change in forest landscapes can be relatively linear, or non-linear. Over time, as human populations and cultures shift and impose new pressures on landscapes, ecological conditions in landscapes change, imposing new limitations and opportunities for people (Gross and Blasius, 2008; Norgaard, 1994; Rammel et al., 2007); people, in turn, adjust their management systems to changing ecosystem characteristics (Bodin et al., 2016a; Liu, Dietz, Carpenter, Folke, et al., 2007b; Österblom et al., 2010; Reenberg et al., 2008; Sivapalan and Bloschl, 2015). Humans can also change entire forest landscapes with long-lasting impacts through disproportionately small actions at single points in time, for example, by lighting a fire, or bringing an invasive plant, pest or disease into an uncontaminated stand. This combination of linear and non-linear interactions between social and ecological components across space and time make forest landscapes worthy of study in their own right.

Drawing on emerging empirical and theoretical research literatures from social and natural science fields, I provide a perspective on forest landscapes as SESs, focusing on core processes that govern forest landscapes, specifically feedbacks, time lags, and cross-scale interactions. This interdisciplinary framing emphasizes the biogeophysical and socio-cultural influences on landscapes and the need to consider these influences and the interactions among them over space and time. I identify challenges that can emerge in forest landscape management when these processes are not taken into account, resulting in mismatches in the spatial and temporal scales on which ecological processes occur and humans attempt to govern these processes, as well as opportunities to improve society's institutions for managing forest landscapes by treating them as SESs. Here, I focus in particular on temperate forests, which are undergoing dramatic change in North America and other regions. In offering this perspective on forest landscapes as socio-ecological systems, grounded in a synthesis of emerging literature, I aim to improve understanding of the interactions between people and forests and the implications of these interactions for landscape planning and management.

2. Key features: feedbacks, time lags, and cross-scale interactions

An emerging literature has framed forest ecosystems in terms of complex adaptive system properties (Filotas et al., 2014; Messier et al., 2015; Nocentini et al., 2017; Spies et al., 2014); specifically, heterogeneous conditions, hierarchical structure, ability to self-organize and adapt in response to changing external conditions, openness (not closed off from other systems), path dependency, non-linearity, and unpredictability (Levin, 1998). In addition, a growing body of empirical research has documented complex interactions between forest ecosystems, socio-economic changes, and land uses over space and time, specifically how new land uses can combine with legacies of past practices and ongoing climate change to give rise to large scale disturbance patterns (Allen, 2007; Barbier et al., 2010; Chapin et al., 2008; Lambin and Meyfroidt, 2010; Ravenscroft et al., 2010; Rudel et al., 2005; Spies et al., 2014; Stanfield et al., 2003; Vergara and Armesto, 2009; Zheng et al., 2010). These bodies of literature provide a foundation for framing forests as SESs. However, despite growing recognition of the complex social and ecological dimensions of forest landscapes, little attention has been paid specifically to core processes that govern forest landscapes as SESs: feedbacks, time lags, and cross-scale interactions. Here I distill and explain these three core processes, and illustrate how recognition of these processes can inform time horizons and spatial extents of management as well as consideration of unintended consequences of management actions (Virapongse et al., 2016).

2.1. Feedbacks

The modification or control of a process or system by its effects – or feedback – is a core SES process that features prominently in forest landscapes. Through feedbacks, forest landscapes self-organize (Filotas et al., 2014). As a type of SES, forest landscapes display feedbacks with both social and ecological dimensions. Many of the current ecological health crises in temperate forests are illustrative of SES feedbacks. Across the temperate forest biome, management activities intended to increase forest productivity for human benefit (thinning, harvesting, road building, fire suppression) have stressed, homogenized, and introduced invasive species into forest landscapes, resulting in large scale wildfires and insect and disease outbreaks that have, in fact, decreased productivity (Millar and Stephenson, 2015). In fire-prone temperate forests, in particular, wildfire risk mitigation activities have amplified the very processes that created risk in the first place; fire suppression has allowed more flammable vegetation to accumulate on forest landscapes, leading to larger and more intense wildfires (Adams, 2013; Calkin et al., 2015; Fischer et al., 2016) (Sidebar 1). On a global scale, forest mortality resulting from increasingly extensive and severe pest outbreaks has led to higher emissions of terrestrial carbon into the atmosphere, further exacerbating global warming (Flower and Gonzalez-Meler, 2015).

Sidebar 1. Feedbacks in dry conifer forest landscapes.

Photo credit: Coconino National Forest

In the western US, accumulation of flammable forest vegetation combined with selective logging of large, fire-resistant tree species and widespread infilling with small-diameter shade-tolerant tree species have set forests up for large, uncontrollable fires under changing climatic conditions (Stavros et al., 2014; Stephens et al., 2013). Where human populations have settled in fire-prone forests, land managers have often chosen to suppress fire rather than use fire as a management tool (Fischer et al., 2016; Johnson and Beale, 1998; Theobald, 2001), allowing flammable vegetation to further accumulate, driving larger and more severe fires (Chapin et al., 2008; Fischer et al., 2016). The destructive fires that now affect dry conifer forest landscapes can be viewed as a feedback of management practices and policies intended to protect people and resources from wildfire. Social components of SESs also self-organize through feedback effects. As large wildfires have become more frequent in the western United States, and markets for forest products have declined, stakeholder groups have re-negotiated goals and means of forest management in some locations (Abrams et al., 2017a,b; Coughlan, 2003; Fischer et al., 2016). In Oregon, for example, community-based organizations, environmentalists, the timber industry, and public land management agencies have worked together to create opportunities for thinning to reduce wildfire risk and restore forests, and to prevent forest product mills, which make thinning economically viable, from closing (Abrams et al., 2017a,b). Moreover, they have promoted use of fire as a management tool and the harvesting of larger diameter trees in dry forests, all of which were unthinkable in the latter half of the 20th century (Coughlan, 2003; Fischer et al., 2016; Ryan et al., 2013; Wimberly and Liu, 2014). This self-organization within the local social system (as opposed to a top-down policy intervention) is an example of an SES feedback, in this case a negative feedback in that it gives rise to practices that reduce wildfire risk and increase market value of byproducts from forest restoration.

2.2. Time lags

In the context of landscapes, time lags refer to the intervals between landscape conditions and the human-nature interactions that lead to them (Antrop, 2005; Liu et al., 2007a; Marcucci, 2000). The concept of time lags is especially critical in forest landscapes because of the longevity of trees – the outcomes of current forest management actions may be evident for decades if not centuries. Because of time lags, forest landscapes can be considered cultural or social artifacts – things created by humans that convey information about past social conditions and behaviors of individuals and groups (Greider and Garkovich, 1994; Nassauer, 1995). The behaviors that people engage into use or manage landscapes are powerfully influenced by broader cultural conventions and customs (Nassauer, 1995), which often go unexamined for long periods of time (Berger and Luckmann, 1967). Time lags allow forests to accumulate information about past cultural conventions and customs to affect the future, i.e., to be path-dependent (Filotas et al., 2014). The iconic oak woodland and savanna landscapes of the US West and Midwest provide an example of time lags; present conditions in these landscapes – highly valued for aesthetic and ecological reasons – are strongly shaped by past cultural conventions and customs in ways that have gone largely unnoticed until recently (Sidebar 2).

Many present-day forest health problems in temperate forests around the world can be considered lagged effects of past practices: fire suppression, road building, grazing, and forest thinning and harvest activities (Castello et al., 1995; Hessburg et al., 2004; Jules et al., 2002; Keeley, 2006; Millar and Stephenson, 2015; Mortensen et al., 2009). As natural resource-based economies decline and rural communities become oriented around amenities and services, new legacies are being created that interact with and complicate former legacies (Rudel et al., 2010). The wildfire crisis in the US West is a lagged effect of management practices that allowed flammable vegetation to accumulate and human populations to settle along flammable forest fringes (Chapin et al., 2008; Fischer et al., 2016; Spies et al., 2017) (Sidebar 1). In a counterexample, rural exodus in southern Europe has led to the abandonment of land management activities and the regrowth of forests containing extensive flammable vegetation that now fuel wildfires (Moreira et al., 2011). In Northwestern Canada and USA, the current epidemic of bark beetles can be attributed, in part, to a century of management practices that have homogenized forest conditions, leaving trees vulnerable to drought stress (Raffa et al., 2008). Combined with global climate change, future effects of past and present forest management practices may be far reaching in time and space (Calkin et al., 2015; Dukes et al., 2009; Hessburg et al., 2004; Ravenscroft et al., 2010; Stephens et al., 2013). In Central Europe, where temperate forests are considered quite resistant to invasive species, recent research suggests that lags between introduction and outbreaks are quite long, indicating that a large invasion debt has potentially not yet been realized (Essl et al., 2012).

Sidebar 2. Time lags in oak woodland and savanna landscapes.

Photo credit: Greenbelt Land Trust

The history of oak (*Quercus* spp.) woodlands and savannas in the US West and Midwest illustrates how present forest landscapes are products of past human-environment relationships. Native American tribes in these regions historically maintained open oak landscape structure with the practice of understory burning, which kept competing shrubs and trees at bay (Boyd, 1999; Dorney and Dorney, 1989; Nowacki et al., 2012). Later, European settlers caused major changes in fire regimes throughout North American forests by logging trees to clear land for agriculture and generate fuel for heating and power. Slash burning sometimes contributed to large wildfires that altered forest landscapes

(Haines and Sando, 1969; Pyne et al., 1996; Robbins, 1997). Other forms of human management such as agriculture and resource extraction acted as long-term drivers in oak forest structure and species composition as well (Black et al., 2006; Nowacki et al., 2012). In the mid-20th century, fire suppression became the dominant response to wildfire in federal, state, and private forest management (Adams, 2013; Busenberg, 2004; Ryan et al., 2013). Without fire, oak stands have experienced declining regeneration in many areas (Knoot et al., 2009; Nowacki and Abrams, 2008) and have developed into stands dominated by other species such as Douglas-fir (*Pseudotsuga menziesii*), which would have historically succumbed to fire, in the Pacific Northwest and maple (*Acer spp*) in the Upper Midwest. Until recently landowners did little to intervene in this transformation of oak woodlands and savannas, typically considering oak as a secondary species (Fischer and Bliss, 2009; Knoot et al., 2010; Knoot et al., 2009). In the Pacific Northwest – once the nation's timber basket – natural resource professionals at one time encouraged private landowners to convert oak woodlands to Douglas-fir or other uses, and some landowners felt a moral obligation to grow Douglas-fir trees, even on marginal sites, to fulfill the notion of good stewardship (Fischer and Bliss, 2009). Recently, oak restoration has become a common management objective for public and private landowners alike (Fischer and Bliss, 2009; Knoot et al., 2010; Knoot et al., 2009). In the Pacific Northwest, this shift may be attributable to the co-occurrence of two events that prompted a re-examination of how society values private forest land and different forest types: a proposal to list several oak woodland and savanna-associated species as endangered, and a decline in market incentives to grow Douglas-fir. Few policies have incentivized oak management, although policies have been explored (Oregon Watershed Enhancement Board, 2010; Tucker, 2004). Rather, the emergence of oak management among private and public landowners is likely attributable to a slow change in landowners' attitudes, values, goals, and social norms regarding land management.

2.3. Cross-scale interactions

Forest landscapes can be viewed as spatially nested, temporally interdependent sets of social and ecological conditions and processes (Rammel et al., 2007). In this way, forest landscapes are hierarchical: ecological patterns in forest landscapes are a function of interactions with social systems at local and regional levels (Filotas et al., 2014; Messier et al., 2015; Peters et al., 2004; Soranno et al., 2014). Human systems interact most directly with landscapes at the level of individuals. At this level, people shape landscapes by engaging in behaviors to take advantage of, or reduce risks to, ecological goods and services that they value, for example, by removing or planting trees to improve wildlife habitat, scenic beauty, recreational opportunities, or forest products. Human systems also interact with landscapes at the level of social groups, where interaction among cohesive sets of similar people shape perceptions and norms of behavior regarding forest management within the group. Similarly, perceptions and norms are shaped through social interaction within broader communities of place (e.g., towns and regions where people live, their schools or workplaces). At population levels, institutional interventions (e.g., policies, organizations, markets) affect the management actions of groups of forest managers (e.g., federal land managers or private noncorporate forest owners). Forests are also open systems; boundaries between processes internal and external to the system are difficult to define (Filotas et al., 2014). The forest management actions of individuals, while implemented on specific landscapes at specific points in time, can have impacts in aggregation that are far reaching in space and time.

Many forest pests and disease problems are a function of cross-scale socio-ecological interactions. The spread of beech bark disease across hardwood forest landscapes in the Northeastern United States, for example, can be attributed to the fine-scale mechanism of individual campsite users unloading contaminated firewood purchased elsewhere (McCullough et al., 2005). In Central Europe, global climate change is driving fine-scale shifts in interactions between drought, windthrow, and spruce bark beetle outbreaks that are expected to result in long-term changes for Norway spruce as a local species (Temperli et al., 2013). In Northwestern Canada and USA, impacts from global climate change have created local conditions in which bark beetles can take advantage of their hosts, leading to large outbreaks across vast areas (Raffa et al., 2008). Fire-prone forests provide a particularly clear case of cross-scale interactions. In such forests, the probability of a wildfire igniting and the severity of a burn, are a function of the composition and distribution of flammable vegetation on the broader landscape, and sometimes of conditions distant from a forested stand (Ager et al., 2012). Ignitions or incursions on an individual property, if not attended to, can result in large-scale events affecting many properties in relatively short periods of time. This phenomenon has been documented across the temperate forest biome, and in particularly catastrophic events in Europe, Australia, and western US and Canada (Bowman et al., 2011; Millar and Stephenson, 2015; Stephens et al., 2014).

3. Management Challenges: Scale mismatches

One of the reasons that feedbacks, time lags, and cross-scale interactions are so important to consider as part of the management of forest landscapes is that society's governing institutions often function on different spatial and temporal scales than natural systems. These discordant scales of ecological and social processes can lead to a lack of correspondence in human and ecosystem behavior. The theory of institutional fit suggests that mismatches in patterns of environmental variation and social organization for management can result in disruption, inefficiencies, and failures in system functions (Cumming et al., 2006; Farrell and Thiel, 2013; Guerrero et al., 2013; Ostrom, 2010; Young, 2002).

3.1. Temporal scale mismatch

Forests experience reoccurring moderate-to-severe disturbances, both natural and human-caused, that drive ecosystem patterns and processes (Nocentini et al., 2017). The lifespan of trees and the length of return intervals for forest disturbances, often decades or centuries, can make it difficult for humans, whose planning horizons typically span several years or decades, to plan accordingly (Kondolf and Podolak, 2014). Asynchronous timeframes of human response to landscape change may be a root cause of forest health problems such as wildfires and pest and disease outbreaks. Without decision-making frameworks that encourage consideration of potential adverse events in forest landscapes in the future, people may come to rely on ecological conditions and processes that change over time. For example, land use zoning regulations, insurance, and publically-provided wildfire protection have encouraged people to build houses in forest landscapes that are susceptible to large wildfires and large scale pest and pathogen-caused mortality (Flint et al., 2009; Mockrin et al., 2015; Patriquin et al., 2007; Sturtevant et al., 2009). Although some societies have developed mechanisms for remembering environmental changes and events that occur infrequently (e.g., activities to mark past earthquakes and volcanic eruptions), many people have difficulty keeping such constraints in mind (Kondolf and Podolak, 2014). Not realizing that a landscape is controlled by a disturbance regime with a long return interval may lead to human behaviors that exacerbate a problem and its future impacts. For example, economically valuable conifer species such as spruce are vulnerable to wind throw in some areas of Europe; land managers who are not aware of the potential for infrequent but very severe windstorms might favor such tree species at the risk of large scale losses, as Sweden experienced in 2005 (Lidskog and Sjödin, 2014). In fire-prone forests, many people have become exposed to damages from wildfires as a result of policy decisions to suppress wildfires, facilitate population growth in areas where flammable vegetation has

accumulated, and permit people to engage in activities that ignite fires (e.g., campfires and motor vehicle use) (Fischer et al., 2016; Moritz et al., 2014).

3.2. Spatial scale mismatch

There is also a disconnect between the spatial scales on which landscapes and humans function, and this too poses a challenge to managing forest landscapes as SESs. It is well-recognized that administrative boundaries established by society often do not conform to ecological boundaries (Landres et al., 1998). This is especially true with forest landscapes, which, because of their extensiveness, often contain multiple overlapping and competing social territories; territories of agencies and institutions with different mandates and laws, and territories of communities with different economics and activities that depend on natural resources (Powell, 2010). In landscape ecology and natural resource planning, landscapes are often demarcated on the basis of ecological attributes, as in the example of watersheds and ecoregions. This act of identifying differentiations or discontinuities in ecological structure and function suggests that landscapes can be demarcated independently of human cognition and behavior (Smith, 1995). This contrasts with a sociological view of landscape boundaries as geographic footprints of human decision-making (Smith, 1995). From this perspective, the boundaries humans impose on maps represent features of landscapes that people value and from which people derive their sense of identity (Fall, 2003). Humans tend to develop connections to place at small scales based on social, historical, and cultural circumstances (Fall, 2003; Powell, 2010). Indeed, forestry in the United States, Australia, and Europe, for example, has historically been largely practiced at the stand-level without consideration of interacting factors embedded in the wider spatial context (Holdenrieder et al., 2004). Many geographic units that are socially coherent seem arbitrary when considered in relation to biophysical conditions and processes and the temporal and spatial scales on which ecosystems function (Smith, 1995); they thus lack institutional fit (Epstein et al., 2015). Moreover, socially coherent units may involve a variety of fragmented non-overlapping areas that can actually exist on multiple scales depending on one's frame of reference for an issue.

4. Management opportunities: institutional interventions

Change in forest landscapes is a slow process punctuated by rapid and surprising shifts, or threshold crossings (Liu et al., 2007a). Moreover, forest landscape change is the result of complex social and ecological drivers that interact across space and time. Because social conventions and customs that govern land management tend to go unexamined for long periods of time, humans find it difficult to recognize how they shape forest landscapes (Berger and Luckmann, 1967; Greider and Garkovich, 1994; Nassauer, 1995). Sudden ecological shifts may prompt people to reflect on how and why specific management approaches have resulted in certain landscape conditions. Well-designed policies, organizations, and governance networks may facilitate this process by encouraging people to recognize current ecological conditions and events as a function of past land use and land management behaviors, and anticipate future undesirable feedbacks, lagged effects, and cross-scale interactions. By improving the fit between human behavior and ecological systems, such institutional interventions may encourage people to adopt practices that are appropriate for the temporal and spatial scales on which ecosystem processes occur, arguably increasing social capacity to manage forest landscapes as SESs (Cumming et al., 2006; Farrell and Thiel, 2013; Guerrero et al., 2013; Ostrom, 2010; Young, 2002). Although recognition of the spatially diffuse and enduring nature of forest dynamics has led to an increasing emphasis on management at landscape scales in the research literature (Brunckhorst, 2011; Knight & Landres, 1998; Powell, 2010), institutional interventions to compel management at such scales are just beginning to emerge. Here I highlight policies, formal organizations, and governance networks that hold promise for promoting landscape management in temperate forests.

4.1. Policies

Several policy innovations have been developed to foster landscape management in temperate forest countries. In the United States, a number of federal agencies have made formal commitments to support management across ownership boundaries on landscape scales in cooperation with other agencies and private landowners (Lubell, 2004; U.S. Department of the Interior, 2011; USDA, 2010). In practice, the US Collaborative Forest Landscape Restoration Program (CFLRP) supports coordinated planning for forest landscapes, although program funding can only be used for the management of federal land (Schultz et al., 2012). The National Cohesive Wildland Fire Management Strategy, also in the US, promotes collaboration between government and non-governmental organizations and the public in "all lands" approaches to forest restoration and fire protection (Wildland Fire Leadership Council, 2016). Two policies allow federal agencies in the US to fund and implement management actions on adjacent public and private land as part of coordinated landscape-scale strategies: the federal Two Chiefs' Joint Landscape Restoration Partnership to improve the health of forests at the public-private interface, and the Wyden Amendment, which authorizes the Forest Service to enter into cooperative agreements with other public, private, tribal, and nonprofit entities to conduct activities to conserve habitat or reduce natural hazards on public or private lands (Charnley et al., 2017). In Europe, Close-to-Nature Forestry, a broad approach rather than a program, treats the landscape as an important unit for management (Nocentini et al., 2017). In Italy a Forest Landscape Management Plan policy shifts forest planning from a parcel level to a regional and landscape level, and mandates public participation (Paletto et al., 2012; Paletto et al., 2015). Systemic forestry and resilience thinking are approaches to forestry that accommodate forests as SESs (Nocentini et al., 2017; Rist and Moen, 2013), but have not yet been instituted through policy. All the above initiatives advance the notion of managing forest landscapes as SESs by fostering management of forest landscapes on spatial scales that are larger than the typical public and private ownership. While these initiatives can help account for potential cross-scale interactions and prevent spatial scale mismatches, they do not explicitly address the temporal dimensions of SESs, specifically time lags and feedbacks.

4.2. Organizations

In the past decade, researchers have proposed novel organizations as a way to extend both spatial and temporal scales of forest management. These approaches have included knitting together existing types of property – public and private – to facilitate management across ownership boundaries; creating nested sets of management organizations at multiple ecological scales; and creating agreements to manage certain forests, such as community forests, as common property (Brunckhorst et al., 2006; Goldman et al., 2007; Powell, 2010). In southeast Australia, for example, eco-civic planning units have been proposed to maximize three conditions that are considered requisites for landscape management: biophysical features that possess a high level of homogeneity; boundaries that maximize the area that people connect with; and a nested, multiscalar capacity for optimizing decision making (Brunckhorst et al., 2006). Management districts that allow landowners to jointly receive cost-share funds and coordinate activities without individual legal liability have also been proposed as a way to incentivize landscape management (Goldman et al., 2007).

In practice, few of the formal organizations that have developed around landscape management operate as governing bodies of forest landscapes. Even in the context of fire-prone forests, where lack of institutional fit has proved very problematic, the emergence of landscape-

scale management organizations, until recently, has been rare (Charnley et al., 2017; Fischer and Charnley, 2012a,b; Powell, 2010). Rather, organizations have largely focused on planning. Forestry cooperatives, for example, which have been popular at times in Europe, Japan, New Zealand, and to some extent, the US, have aggregated multiple landowners to increase economies of scale for marketing timber and insuring against individual losses (Blinn et al., 2007; Rickenbach, 2009; Wolf and Hufnagl-Eichiner, 2007). Public-private partnership organizations have also emerged to promote landscape management (Butler and Goldstein, 2010; Knight & Landres, 1998; Laven et al., 2012), specifically in the areas of large scale conservation planning (Jacobson and Robertson, 2012; Wyborn and Bixler, 2013). Landscape Conservation Cooperatives (LCCs) in the United States, for example, promote regional forest landscape management by providing information and tools to inform collaborative activities and by serving as forums for stakeholders to identify shared management concerns (Jacobson and Robertson, 2012; Jacobson and Haubold, 2014; Landscape Conservation Cooperative Network, 2015). At a small scale, prescribed fire councils and Firewise groups engage landowners, land managers, and other stakeholders in planning processes regarding forest thinning and prescribed burning to reduce wildfire risk across jurisdictional lines (Riechman et al., 2014; Ryan et al., 2013).

Substantial opportunity remains for developing innovative organizations to bring multiple landowners and stakeholders together in the management of shared landscapes. Such organizations will need to reconcile tensions between the need for collaboration and concerns about property rights. Governance structures that supersede property rights will likely not be tenable in countries such as the United States where the institution of private land ownership remains paramount. New landscape management organizations will also need to protect against the risk of conforming to spatial and temporal scales of management that are most convenient for people and becoming rigid and ill-suited to the ecological context (Holling and Meffe, 1996). Organizations tend lose their ability to be responsive to the environment as internal structures become more focused and tightly coupled (Miller, 1993; Westley and Vredenburg, 1997).

4.3. Governance networks

Network governance approaches to landscape management have gained popularity as people have recognized the challenges that formal organizations face in managing landscapes. Governance networks are sets of interacting organizations or actors concerned with a common problem that influence how public decisions are made and carried out (Torfing, 2012). Typically, governance networks emerge in response to a problem and self-organize to address it, although policies and other organizations can initiate them. For example, the Fire Learning Network, an initiative of the US Forest Service and The Nature Conservancy (Butler and Goldstein, 2010), engages loose sets of land management organizations in ecological restoration activities in fire-dependent ecosystems through landscape-scale collaborative planning, regional capacity building, and national coordination (Butler and Goldstein, 2010). Some networks have focused on large landscapes. For example, Roundtable on the Crown of the Continent emerged from interactions among an extensive set of land ownership and stakeholder groups to plan and implement conservation strategies for the geographic area that spans the US and Canadian Rockies. America's Longleaf Restoration Initiative, also composed of an extensive set of groups, aims to restore longleaf pine (*Pinus palustris*) forests within its historic range in the southeastern US (Scarlett and McKinney, 2016).

Researchers argue that governance networks are well-suited to address large-scale multi-jurisdictional problems with social and ecological dimensions, which are often beyond the capacity of individual organizations to address (Bodin and Crona, 2009; Bodin et al., 2016a; Bodin et al., 2016b; Ernstson et al., 2010; Powell, 2010; Wolf, 2011). Several features of networks make them a particularly suitable mechanism to foster management of forests landscapes as SESs. Networks can function as collaborative institutional structures that unite stakeholders into both formal and informal arrangements; their very structure allows them to be flexible and adaptive to respond to changing conditions (Powell, 2010). Further, networks can operate across multiple jurisdictions and geographies (i.e., be multiscalar), have many centers of authority (i.e., polycentric), and comprise local to national stakeholders and institutions (i.e., be multi-level) (Karkkainen, 2004). In some cases, governance networks can arguably create opportunities for communication and collaboration without the need for costly new organizations. This may be beneficial where organizations in the same geographic area are concerned about a common problem yet are not in the habit of directly interacting (Fischer and Jasny, 2017). Finally, networks can overcome fragmentation, facilitate flows of information, and fulfill functions necessary for dealing with cross-boundary issues that traditional ownership-focused organizations cannot (Karkkainen, 2004; Lebel et al., 2006; Olsson et al., 2004; Powell, 2010; Walker et al., 2006).

By virtue of their inherent flexibility, adaptiveness, and ability to accommodate diverse actors, governance networks may address the need for managing forests at the scale of geographic units large enough to support biophysical homogeneity and small enough to capture the area that people consider important (Brunckhorst et al., 2006). At the same time, because governance networks generally form when it becomes evident that existing organizations lack capacity to complete a given task, and costs are too prohibitive to add the necessary capabilities internally (Benjamin et al., 2011), they risk offering too little too late. This lag between need and response may be problematic in forest landscape contexts where planning must take place well in advance of anticipated changes and over long time horizons, for example in the context of slow onset climate-related changes in forest landscapes. Also, without formal processes or binding rules and agreements, governance networks are vulnerable to the domination by special interests (Bixler et al., 2016).

5. Conclusion

As nested sets of coevolving social and natural subsystems connected through time lags, feedbacks, and cross-scale interactions, temperate forest landscapes serve as a classic example of an SES. By considering these core SES processes, forest managers, planners, and policy makers may be able to reconcile the mismatches that so often occur in the spatial and temporal scales on which ecological processes occur and on which humans attempt to govern these processes. Thinking about forest landscapes as SESs may provide perspective during periods of both slow and rapid environmental change. When people realize how management practices in the past, and management practices on different scales, have affected forest landscapes, they may be better able to negotiate and justify decisions to manage for new goals. In the process of negotiating new meanings for landscapes, people's conceptions of their relationships to landscapes may also change (Nassauer, 1995). Indeed, researchers have found that the ability to discern the history of a landscape strongly enhances the planning process for future management (Antrop, 2005; Marcucci, 2000; Palang et al., 2011). Anticipating how ecological processes that result from current forest management behavior will interact across space and time may help people make informed decisions at the finer scales at which they engage in management actions. For example, managers with broad perspectives on landscapes may strive for heterogeneity instead of homogeneity, and multifunctionality rather than singular focus on one or a few values; they may manage at the landscape rather than stand level or at a range of different spatial and temporal scales and deliberately engage the social system with the natural system through various forms of stakeholder participation in decision making; managers may also become more comfortable expecting unpredictable and unintended outcomes, emphasizing

monitoring in addition to forecasting (Filotas et al., 2014; Levin, 1998; Messier et al., 2015; Nocentini et al., 2017).

In practice, coordinating management activities that affect ecological conditions and processes across large and socially-complex spaces has proved challenging and few institutional interventions have successfully been developed and implemented (Briggs, 2001; Charnley et al., 2017; Laven et al., 2012). A suite of institutional mechanisms – policies, formal organizations, and governance networks – will likely be necessary to increase societal capacity to manage forest landscapes as SESs. By making funding and information available, supporting research, creating opportunities for multiple parties to convene and interact, and providing legal assurances and incentives, policies can foster broad scale and long term planning among multiple actors in a forest landscape to anticipate legacy effects and potential cross-scale interactions, disrupt undesirable feedbacks, and reconcile scale mismatches. Formal organizations can ensure continuity and reciprocity among participating parties, thus enabling implementation of SES approaches to landscape management at large scales. In lieu of being able to create new formal organizations in the near term, governance networks are well-suited to foster landscape management because of their flexibility and adaptiveness. A potentially beneficial governance network intervention could be nested networks of public and private landowners that coordinate management for small landscapes and also engage in cross-network interactions to understand implications across spatial and temporal scales. Policies could incentivize such endeavors, and formal organizations could scaffold them. Enabled by a suite of institutional interventions, such hybrid landscape governance models could serve as complements to (rather than substitutes for) existing state and market-based institutions. Over time, these hybrid models can evolve into new formal organizations for managing larger areas over longer time scales.

To develop viable institutional interventions for landscape management, more empirical research is needed to fully specify forest landscapes as SESs. Building on recent interdisciplinary and transdisciplinary landscape research frameworks (e.g., Fry (2001) and Tress and Tress (2001)) and SES research frameworks (e.g., Liu et al. (2007a)), future research could focus on integrating social and natural science methods to characterize types of forest landscapes on the basis of core SES processes, and spatial and temporal mismatches that challenge management. Inventorying a comprehensive set of forest landscape cases and building a typology of SES system components and institutional intervention points, for example, would, in turn, help build SES theories regarding forest landscapes. Further empirical investigation of policies, formal organizations, and governance networks and their outcomes for ecological function in forest landscapes is also critical for advancing the theory of institutional fit. A better understanding of the effectiveness of different institutional interventions for different types of forest landscapes may help people make decisions regarding how to demarcate management areas that make sense ecologically and socially, and coordinate management activities across the ecological and social territories that comprise these areas. Overall, building a more comprehensive theory of forest landscapes as SESs will be critical to increasing our understanding of landscapes and ability to manage them.

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