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A social-ecological network approach for understanding wildfire risk governance

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ABSTRACT

Large wildfire events (e.g. > 100 square km) highlight the importance of governance systems that address wildfire risk at landscape scales and among multiple land owners and institutions. A growing body of empirical work demonstrates that environmental governance outcomes depend upon how well patterns of interaction among actors align with patterns of ecological connectivity, such as wildfire transmission. However, the factors that facilitate or inhibit this alignment remain poorly understood. It is crucial to improve understanding of the conditions under which actors establish or maintain linkages with other actors with whom they are interdependent because of ecological linkages. To this end, we introduce the concept of "risk interdependence archetypes" based on the spatial configurations by which one actor (i.e. a particular organization) is exposed to risk via the actions of another actor. We then develop a set of hypotheses to explore how different sets of conditions associated with each spatial configurations of risk interdependence may shape the likelihood that an actor coordinates with another actor in ways that promote social-ecological alignment. We test these hypotheses using network analysis of a wildfire transmission network developed through simulation of wildfires over several thousand fire seasons and a governance network created from interviews with 154 representatives of 87 organizations involved in efforts to mitigate wildfire risk in the Eastern Cascades Ecoregion, USA. Results indicate that social-ecological alignment is more likely when actors have opportunities to influence forest management practices on ignition-prone lands that they do not manage themselves, and when actors bear greater responsibility for averting losses from wildfires that spread to lands they manage independently. Importantly, not all forms of risk interdependence increase the likelihood of alignment, implying that organizations have limited capacity for interaction and may prioritize certain risk mitigation partnerships over others. While the performance of risk governance systems may hinge on the alignment of social and ecological networks, our results suggest that alignment in turn may depend on actor-level strategies for interaction with other actors.

1. Introduction

There is an emerging consensus that addressing environmental challenges requires coherence between the environmental governance structures and ecological processes that characterize a social-ecological system (Bodin, 2017; Bodin et al., 2016; Bodin and Tengö, 2012; Epstein et al., 2015; Guerrero et al., 2015b; Sayles and Baggio, 2017; Young, 2002). Alignment of structures and processes that span the social and ecological components of a governance system can help mitigate disruption, inefficiencies, and failures in system functions (Cumming et al., 2006; Farrell and Thiel, 2013; Guerrero et al., 2013; Ostrom, 2010; Young, 2002). For example, in rangeland landscapes where invasive plants such as yellow starthistle (*Centaurea solstitialis*) can spread across property boundaries, coordination of land management practices among adjacent ranchers can help prevent new infestations and thereby maintain cattle forage production (Epanchin-Niell et al., 2010). Similarly, the success of traditional Balinese irrigation management institutions hinges upon coordination among farmers throughout the irrigation system, who time water use and rice cultivation practices to optimize water availability and control pest outbreaks (Lansing, 1987). These and other social-ecological systems are characterized by interactions among social actors (e.g., coordination among land managers), among ecological units (e.g., transmission of non-native species among habitat patches), and between social actors and ecological units (e.g., management interventions designed to alter forest composition, or the provision of an ecosystem service to resource

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users). Alignment of these sets of interactions—or "social-ecological alignment"—occurs when there is social interaction among actors that depend upon or influence ecological units that are themselves linked through ecological interactions (Bodin et al., 2014; Cumming et al., 2006).

Social-ecological alignment may be particularly important in governance systems in which hazards are jointly shaped by human and biophysical factors. In these contexts, human activities can influence the biophysical conditions that create hazards in areas often quite distant from where decisions are being made (Ager et al., 2017). For example, in some forest ecosystems, dense flammable vegetation has accumulated because wildfires have been suppressed for many decades by land managers. This vegetation increases one form of ecological connectivity—the potential for transmission of wildfire between forested areas, which may be managed by different individuals or organizations. Because the effects of management decisions such as wildfire suppression are lagged in space and time, people have limited ability to grasp the causes and effects of fires and other hazards (Fischer et al., 2016). Moreover, because people have short tenures in ecosystems relative to the periods over which ecological conditions and processes change, it is difficult for them to react to slow changes in hazardous conditions on large spatial scales (Kondolf and Podolak, 2014). As a result, such systems are prone to institutional fragmentation and the lack of comprehensive approaches to governance at appropriate scales. At the same time, they are also suitable candidates to benefit from approaches to governance that encourage the alignment of social interaction with ecological connectivity, resulting in regional governance systems that better "fit" the environments in which they are embedded (Bodin et al., 2014; Epstein et al., 2015; Treml et al., 2015; Young, 2002).

Despite considerable research on the implications of social-ecological alignment (and misalignment), there is limited understanding of conditions that facilitate or impede interaction among actors that are interdependent because of ecological linkages. Greater understanding of how alignment can emerge as the result of actor-level strategies and behavior is crucial because environmental governance systems typically feature multiple semi-autonomous decision-making processes (Lubell, 2013; Ostrom, 2010), and are therefore resistant to "top-down" centralized interventions designed to increase alignment by directing interaction among interdependent actors. These settings highlight the value of "bottom-up" perspectives that view social-ecological alignment as an emergent outcome of localized patterns of interaction among actors (Cumming et al., 2006; Guerrero et al., 2015a).

In this study, we develop and test hypotheses about the conditions under which individual actors contribute to social-ecological alignment in landscapes in which patterns of ecological connectivity create risk interdependence among actors. We define "risk interdependence" as a condition in which the activities of one actor can expose another actor to risk based on ecological connectivity. Social-ecological alignment thus occurs when an actor "receiving" risk from another actor coordinates with that actor to mitigate risk. We posit that alignment can be a by-product of social processes in which actors create partnerships that offer the greatest opportunities for reducing exposure while minimizing challenges that may hamper risk mitigation coordination (e.g., unfamiliarity with a partner's preferences). In developing specific hypotheses, we propose a set of "risk interdependence archetypes" based on the spatial configurations of wildfire-prone lands managed by different actors.

Our empirical context is a wildfire-prone forested region in Oregon, U.S.A., which provides an ideal setting for evaluating factors that may shape social-ecological alignment. The study system is characterized by strong social-ecological linkages, as numerous organizations manage forested lands, and are likewise affected by wildfire on those lands. Ecological linkages involve transmission of wildfire between lands managed by different organizations and social linkages involve inter-organizational interaction to coordinate wildfire risk mitigation. To account for linkages within and between these social and ecological components, we conceptualize the study system as a social-ecological network (Bodin and Tengö, 2012; Janssen et al., 2006). More specifically, we evaluate hypotheses through analysis of a unique network dataset composed of (1) patterns of risk mitigation coordination among organizations implementing forest and fire management activities within specific jurisdictions, and (2) patterns of wildfire transmission among these jurisdictions, drawn from simulations of fire ignitions and burn perimeters over several thousand fire seasons.

We proceed by describing linkages within and between social and ecological components of the wildfire-prone forested landscape that provides the empirical setting for our study. We then introduce the concept of risk interdependence archetypes and develop a set of hypotheses about how spatial configurations of land management and wildfire transmission shape social interaction in ways that affect social-ecological alignment. We present and discuss the results of a social selection model, which suggest that alignment is most likely when actors are exposed to risk from fires that ignite on lands that they do not manage as well as from fires that burn on lands for which they are solely responsible. We conclude by highlighting implications for network governance of wildfire-prone regions as well as other systems in which ecological connectivity creates interdependence among individuals, organizations, or institutions.

2. Social and ecological connectivity within a wildfire-prone landscape

We study social-ecological alignment in the Eastern Cascades Ecoregion (ECE) in Oregon, USA (Fig. 1). The ECE spans five counties

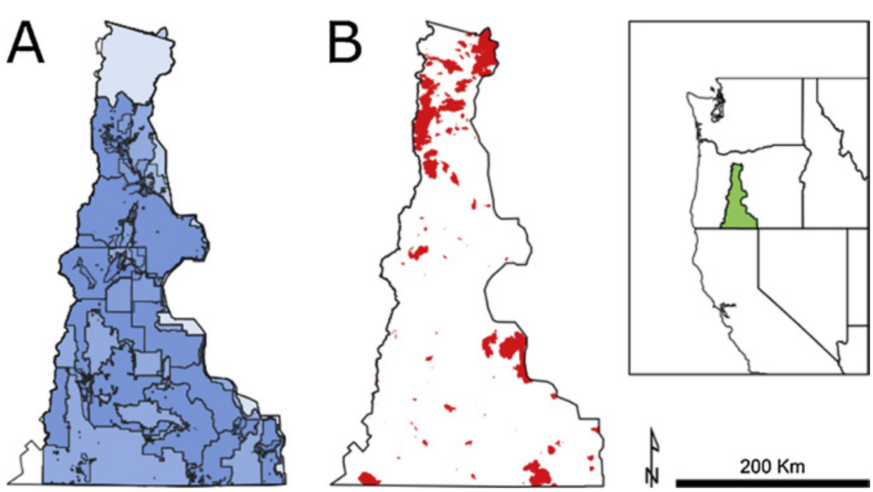


Fig. 1. Maps of the Eastern Cascades Ecoregion. Panel A: jurisdictions within which organizations make decisions about forest and wildfire management. Shading indicates degree to which jurisdictions overlap. Panel B: burned area from recent wildfires (2000–2014); fire perimeter information collected from the GeoMAC historic fire dataset (Geospatial Multi-Agency Coordination Group, 2018).

and approximately 3.3 million ha, and ranges between 500–3260 m in elevation. Dominant tree species include ponderosa pine (*Pinus ponderosa*), lodgepole pine (*Pinus contorta*), western juniper (*Juniperus occidentalis*), mountain hemlock (*Tsuga mertensiana*), Douglas-fir (*Pseudotsuga menziesii*), grand fir (*Abies grandis*), and white fir (*Abies concolor*). Within the ECE, wildfire is a natural ecological process in which fire regimes historically were characterized by frequent low severity fires in lower elevations, as well as higher severity fires in moister forests at higher elevations (Agee, 1993; Merschel et al., 2014).

Contemporary fire regimes within the ECE have been strongly influenced by human activities. Efforts to exclude fire from forests began in the 19th century and became increasingly successful through the end of the 20th century (Merschel et al., 2014), which is in line with broader trends throughout much of the interior western U.S. (Pyne, 1997). Fire suppression contributed to the extensive accumulation of flammable vegetation that would otherwise have been reduced through periodic burning, providing the conditions for “mega-fires” capable of overwhelming suppression efforts while spreading across large areas (Stephens et al., 2014). In these wildfire-prone forested landscapes, land managers now thin stands of trees, conduct understory burns to reduce the amount of flammable vegetation, and remove strips of vegetation to create fuel breaks to prevent fires from spreading from one area to another, among other risk mitigation practices (Charnley et al., 2017; Olsen et al., 2017).

Within the ECE, wildfires with greater potential to burn larger areas are also more likely to spread across management jurisdictions (Ager et al., 2017). We use the term *jurisdiction* to refer to tracts of land in which an organization has the right or responsibility to implement forest or fire management activities. Although approximately two-thirds of the ECE is comprised of federal, state, and local public lands (with the remainder owned by Tribes, timber companies, land trusts, and private landowners), because organizations have different management obligations, their jurisdictions can overlap. For example, within the same tract of land, one organization may mitigate wildfire risk by extinguishing fires after they ignite while another may implement projects to reduce flammable vegetation beforehand. Similarly, even on federal public lands, multiple levels of administrative units that contribute to forest management activities (e.g., US Forest Service ranger districts and national forests) may need to reconcile different management goals and policies about the role of fire in wildland systems. Among the organizations managing land within the study system, only several have private property rights to their jurisdictions and even these organizations do not make all wildfire risk mitigation decisions for the lands they manage. For example, pairs of organizations may share joint responsibilities for fire management on the same land through mutual aid agreements. In these situations, forest or fire management activities undertaken by one organization can affect another organization’s wildfire risk because they jointly manage the same land.

2.1. Archetypes of risk interdependence in complex governance systems

To account for interdependence of wildfire risk in socially complex landscapes in which wildfire may spread across jurisdictional boundaries or burn within areas in which multiple actors’ jurisdictions overlap, we identify four “risk interdependence archetypes” based on the spatial configurations by which a focal actor *i* (i.e. a particular organization) is exposed to wildfire transmitted from lands managed by another actor *j* (Fig. 2). Given the potential for these actors’ jurisdictions to overlap, we distinguish between situations in which wildfire ignites on lands managed independently by actor *j* (archetypes B and D) and lands managed jointly by both actors (archetypes C and A). Likewise, wildfire may spread to lands managed independently by actor *i* (archetypes C and D) or to lands managed jointly by both actors (archetypes A and B). An actor may be exposed to different levels of wildfire risk from another actor via one or more of these archetypes. For example, any fire that burns within land managed independently and that ignited on lands managed jointly with another actor (i.e., archetype C) will also burn a portion of that jointly managed land (i.e., archetype A). Rather than differentiating pairs of actors according to one archetype or another, we use the archetypes to characterize an actor’s profile of risk from fires transmitted from another actor (e.g., 45% from archetype A, 10% from B, 35% from C, 10% from D).

The common feature in all archetypes is that wildfire ignites in a jurisdiction managed at least in part by actor *j* and spreads to a jurisdiction managed at least in part by actor *i*. Therefore, social-ecological alignment occurs in its simplest form when actor *i* establishes a relationship with actor *j* to coordinate wildfire risk mitigation efforts in some way. Because actor *i* selects actor *j*, and because wildfire spreads from one area to another, we recognize social and ecological relationships as “directed”, rather than bilateral or reciprocal. In many cases, there may be a reciprocal relationship between the actors. Likewise, just as wildfire may spread from actor *j*’s jurisdiction to actor *i*’s jurisdiction, the opposite may be true as well. However, the most basic representation of social-ecological alignment involves a directed social relationship contingent on a directed ecological relationship (i.e., the configurations depicted in Fig. 2A–D). Although simple, these configurations can serve as building blocks for understanding broader patterns of social and ecological interaction at the level of the overall governance system (Bodin et al., 2014).

We focus on social-ecological alignment as a consequence of *social selection*, which refers to the process by which actors form relationships based on the characteristics of other actors (Robins et al., 2001). Actors may prefer certain partners based on whether and how they are exposed to wildfire transmitted from lands managed by those partners. In the following four hypotheses, we describe why we expect actors to coordinate risk mitigation with partners that expose them to risk via each of the four risk interdependence archetypes.

H1. The likelihood that an actor *i* establishes a relationship with another actor *j* to coordinate wildfire risk will increase as a function of actor *i*’s exposure to fires that ignite and burn within land jointly managed by both actors *i* and *j* (i.e., risk interdependence archetype “A”; Fig. 2A)

Consistent with this hypothesis is our expectation that actors select partners on the basis of familiarity and shared values, which are likely to be greater among actors whose jurisdictions overlap. In particular, proximity may facilitate in-person meetings and other forms of interaction that increase familiarity and thereby help actors more easily work together (Wondolleck and Yaffee, 2000). Additionally, actors that jointly manage the same resource base are more likely to have similar values, in part because of greater opportunities for social interaction (Gray, 1985), but also because they are more likely to share the same place-based identity (Wondolleck and Yaffee, 2000). Wildfire threatens different values, which include human life, health, homes and other structures, timber, biodiversity and ecosystem services, scenic values, recreational opportunities, and cultural resources (Brenkert-Smith and Champ, 2011; Carroll and Paveglio, 2016; Fischer et al., 2014; Gordon et al., 2013; McCaffrey et al., 2011). When actors share the same values, it is easier for them to reach agreements (Gruber, 2010; Schusler et al., 2003), which may otherwise require protracted negotiations (e.g., over the design of a fuels reduction project). The reasoning behind H1 extends beyond the well-documented relationship between proximity and social selection (Greenbaum and Greenbaum, 1985; Rice and Aydin, 1991; Zahn, 1991). While we generally expect that an actor will select partners on the basis of joint management (and our analysis controls for this potential tendency), we expect the likelihood of a partnership to increase as function of exposure to wildfire on those jointly managed lands. This expectation is consistent with evidence that actors are able to perceive wildfire risk from certain environmental cues such as the density of understory vegetation (Fischer et al., 2014; Olsen et al., 2017) and are more likely to utilize social relationships to coordinate

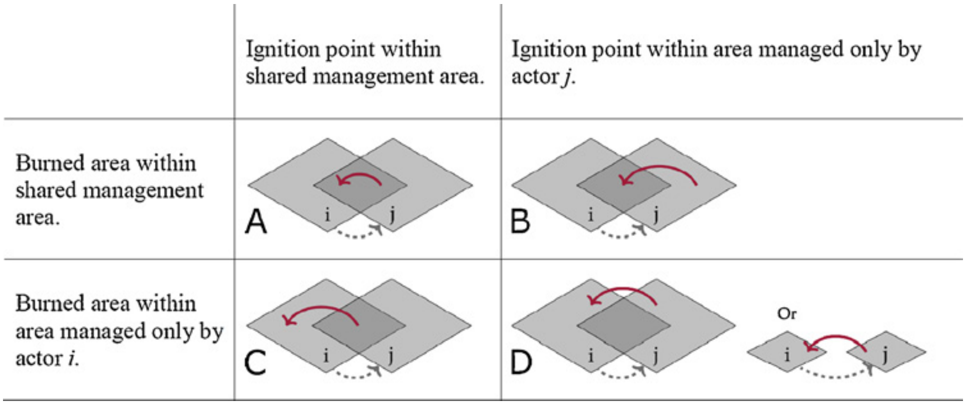


Fig. 2. Four archetypes of risk interdependence that create opportunities for social-ecological alignment. Solid red arrows depict potential ignition and transmission of wildfire. Shaded areas indicate management jurisdictions of actors, and darker shading indicates jointly managed land. Social-ecological alignment occurs if actor *i* coordinates with actor *j* (dashed grey arrows) regarding management activities that would reduce *i*'s exposure to wildfire transmitted from land at least partially managed by *j*. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

risk mitigation when they perceive hazard conditions to be greater (Dickinson et al., 2015; Fischer and Charnley, 2012). However, it is important to distinguish between an actor's ability to perceive and respond to "localized" risk (e.g., within the actor's jurisdiction) and risk from more distant hazards, which may additionally be prone to temporal lags (Fischer et al., 2016).

H2. The likelihood that an actor *i* establishes a relationship with another actor *j* to coordinate wildfire will increase as a function of actor *i*'s exposure to fires that ignite within land managed by actor *j* and burn within land jointly managed by both actors *i* and *j* (i.e., risk interdependence archetype "B"; Fig. 2B)

For the same reasons we outline in H1, we expect actors to select partners on the basis of familiarity and shared values, which are more likely among actors that manage land together. However, in contrast to archetype A, which motivates H1, in archetype B, an actor is exposed to risk from fires that ignite on lands that are not jointly managed with a prospective partner (Fig. 2B). For this reason, the effect of joint management may primarily facilitate coordination in the context of wildfire response, rather than prevention. Wildfire response situations are prone to information asymmetries among actors, which can inhibit effective communication (Steelman et al., 2014), especially given the tendency for the group of responding actors to change several times over the course of an individual wildfire (Nowell et al., 2017). Familiarity can not only function to mitigate information asymmetries, but can also help actors navigate the complex divisions of labor inherent to wildfire incident response, which features numerous interdependent tasks (e.g., maintaining a supply of materials and utilizing those materials to protect assets from fire) (Bodin and Nohrstedt, 2016). In wildfire response settings, knowledge of the capabilities of prospective partners can help actors avoid carrying out tasks that are redundant or interfere with tasks undertaken by other actors. Likewise, coordination of wildfire response can also involve difficult decisions, often under conditions of considerable uncertainty, about the allocation of firefighting equipment and other assets to protect one resource at the expense of another (Thompson and Calkin, 2011). When actors select partners that share their values, they may be better able to reach mutually agreeable tactical decisions. Finally, we recognize that actors may seek partners that independently manage lands where wildfire ignites, because social interaction offers opportunities for actors to influence land management practices of other actors (Fischer and Jasny, 2017). From the perspective of an actor evaluating partnerships with actors that do not manage lands where wildfire can ignite and spread to the actor's jurisdiction, partnerships with actors who do manage these ignition-prone lands may be preferable because they offer opportunities to shape decisions about forest management (e.g., fuels reduction projects) on those ignition-prone lands, thereby reducing the actor's exposure to wildfire risk.

H3. The likelihood that an actor *i* establishes a relationship with another actor *j* to coordinate wildfire will increase as a function of actor *i*'s exposure to fires that ignite within land jointly managed by both actors *i* and *j* and burn within land managed by actor *i* (i.e., risk interdependence archetype "C"; Fig. 2C)

Here, we again draw upon reasoning outlined in H1 to motivate our expectation that actors will select partners on the basis of familiarity and shared values, which are more likely among actors that manage land together. However, for H3, we expect actors to assess partnerships on the basis of exposure to risk from fires that ignite on lands jointly managed with prospective partners (Fig. 2C), where fuels reduction and other preventative measures could reduce the likelihood that fires spread to lands managed independently of those partners. Consequently, we expect joint management of ignition-prone lands to primarily facilitate coordination in the context of wildfire prevention, rather than response. While wildfire prevention partnerships offer opportunities to conduct activities such as fuels reduction at scale (Goldstein and Butler, 2010), they also introduce challenges such as the commitment of time needed to reach agreements about project design (Sturtevant, 2006) as well as the need to monitor activities undertaken by partners—often in areas that are difficult to access—to ensure they are implemented as designed (Canadas et al., 2016; Gass et al., 2009). Actors may be able to mitigate these challenges by selecting partners with whom they jointly manage ignition-prone lands. Through more frequent interaction, facilitated by this proximity, actors may become more familiar with these prospective partners' preferences for forest management, which can facilitate decision-making (Wondolleck and Yaffee, 2000). Familiarity with the capabilities of prospective partners may likewise increase actors' confidence that activities will be implemented as agreed (Gass et al., 2009; Lubell, 2007), thereby increasing the value of the partnership.

H4. The likelihood that an actor *i* establishes a relationship with another actor *j* to coordinate wildfire will increase as a function of actor *i*'s exposure to fires that ignite on land managed by actor *j* and burn within land managed by actor *i* (i.e., risk interdependence archetype "D"; Fig. 2D)

Unlike the other archetypes of risk interdependence, archetype D (Fig. 2D) does not feature joint management of lands that are ignition-prone and/or exposed to fire. Hence, we do not expect partnership selection to be more likely based on familiarity or shared values. However, because an actor can influence other actors' forest management practices (Fischer and Jasny, 2017), these partnerships can provide opportunities to influence forest management activities on lands where wildfire can ignite and subsequently spread an actor's own jurisdiction (Bergmann and Bliss, 2004). Indeed, private forest managers have been shown to coordinate with public forest managers when private lands are at risk of fires transmitted from public lands (Fischer and Charnley, 2012).

Although we expect that actors will prefer partners managing lands that expose their own lands to wildfire risk, these hypotheses distinguish between sets of conditions—associated with spatial configurations of risk interdependence—that may shape social selection in different ways.

3. Materials and methods

3.1. Social network of risk mitigation coordination among actors

Three rounds of snowball sampling were conducted to identify the network of organizations involved in management of forests and wildfire in the Eastern Cascades Ecoregion (ECE). The research team first identified a sample seed of 45 individuals. Based on their experience working in the study system, members of the research team considered these individuals to be key actors. The snowball culminated with 154 respondents who collectively represented 87 organizations. Through semi-structured interviews, representatives of these organizations provided a range of information about perceptions of the role of wildfire in forests and attitudes towards wildfire and forest management practices. Respondents also identified the organizations with which their organization had interacted in the previous year on forest or wildfire management activities. Specifically, the interview prompted respondents to identify 1) organizations with which they collaborate to fund, implement, or plan activities, and 2) organizations from which they obtain information or expertise. Respondents were more selective in identifying partners from whom they obtained information or expertise (3.7% of all possible links were present) compared to those with whom they worked with to fund, implement, or plan activities (10.4% of all possible links were present). We combined both relationships into a single measure of risk mitigation coordination such that a tie from organization i to organization j indicated that i identified j as a collaborator as well as an organization from which it obtained information or expertise. Our approach in operationalizing coordination (i.e., as contingent on both these relationships) is informed by scholarship on inter-organizational governance of risk as well as network governance more generally. When actors coordinate to mitigate risk, successful outcomes not only hinge upon the integration of distinct knowledge bases, but also the collective utilization of diverse capabilities (Comfort and Kapucu, 2006; Janssen et al., 2010). For example, in the context of wildfire response, actors coordinate with other actors to seek information about the local terrain, infrastructure, availability of resources, and updates about the behavior of the fire itself, while jointly planning activities in such a way as to avoid duplication (Bodin and Nohrstedt, 2016; Nowell et al., 2017). Likewise, when coordinating to undertake forest management activities designed to reduce hazardous conditions, actors seek to align their management strategies (which requires information about other actors' strategies) in order to better implement actions in partnership with other actors (Charnley et al., 2017; Spies et al., 2014). Just as scholarship on inter-organizational risk mitigation conceptualizes coordination in terms of these social activities (i.e., seeking information/expertise and jointly carrying out activities), the broader literature on network governance likewise informs our focus on coordination in terms of the types of challenges that actors confront. In particular, this literature draws a theoretical distinction between coordination and cooperation dilemmas. In coordination dilemmas, actors have little incentive to misrepresent their preferences or doubt the credibility of partners' intentions; the challenge relates to acquiring information necessary for designing and implementing harmonized actions rather than convincing or coercing others to join the group effort (Termeer et al., 2010). By contrast, cooperation dilemmas arise when actors are prone to defect from joint agreements or actions out of self-interest (Berardo and Scholz, 2010; Feiock, 2009). Although wildfire risk introduces the potential for defection in the form of free-riding (Busby et al., 2012), among the organizations we study, collaboration (i.e., joint funding, implementation, and planning) is less constrained by lack of credibility of others' commitments so much as institutional and regulatory barriers that limit joint action across complex multi-jurisdictional landscapes (Fischer and Jasny, 2017). Likewise, in our empirical context, actors primarily obtain information from other actors to more efficiently coordinate decision-making rather than to reduce their exposure to exploitation by actor that misrepresent their preferences or intentions (Berardo and Scholz, 2010).

Given our objective to assess coordination among actors directly exposed to wildfire, we restricted our analysis to actors that conducted forest and/or fire management within spatial jurisdictions. Using interview data, public records, and knowledge from local experts, we identified from the original roster of 87 organizations a subset of 36 such organizations. Among the organizations without jurisdictions, which were excluded from the analysis, some sought to influence land management or community-level preparedness though advocacy and outreach while others contributed to forest or fire policies at higher administrative levels. Among the 36 organizations included in the sample, there were several cases of nested relationships (e.g., the Sisters Ranger District is a subunit of the Deschutes National Forest). While such relationships complicate the conceptualization of the study system as a network of actors, we opted to recognize "units" and "subunits" as separate actors because units/subunits have distinct staffs, buildings, jurisdictions, and programmatic objectives, and because respondents themselves distinguished between units/subunits when interviewed.

3.2. Ecological network of wildfire transmission among actors' jurisdictions

In order to measure wildfire transmission among actors' jurisdictions, we first needed to map actors (i.e., organizations) to the landscape. We delineated the boundaries of organizations' management jurisdictions using data from the Oregon Spatial Data Library (OSDL, 2016) as well as the Oregon Department of Forestry Maps and Data clearinghouse (ODF, 2016). For a subset of organizations, spatial data were not publicly available. For these organizations, we located maps included in reports (e.g., pdf documents), which clearly outlined their jurisdictional boundaries. Maps were then georeferenced and boundaries were delineated by hand in ArcMap (ESRI, 2015). Because organizations' jurisdictions overlapped extensively, we created one spatial layer of the intersection of all jurisdictions, which yielded 305 polygons, each of which was managed in its entirety by one or more actors.

To model the transmission of wildfire among these polygons, we used FConstMTT, a command line version of FlamMap (Finney, 2006), which simulates wildfires using a minimum travel time algorithm (Finney, 2002). We used a spatiotemporal ignition model that predicted daily ignition location and fire size based on empirical relationships between energy release component (ERC) and historical fires (11,618 ignitions) (Ager et al., 2018). Historical ignition data (1992–2009) were obtained from the CONUS spatial wildfire database (Short, 2014). Daily ERC data were downloaded from the RAWS USA Climate Archive for 25 remote stations in the study region and values were averaged by day of ignition. Burning conditions associated with each ignition were also obtained from historical conditions as described in Ager et al. (2018).

We simulated 3000 fire seasons for a total of 63,736 fire events, sufficient to burn every burnable pixel at least 10 times. Using output from these simulations, we calculated the area burned within each polygon (i.e., area within the study region managed entirely by one or more organizations) by fires that ignited on each of the other polygons. Accounting for which actor(s) managed each polygon, we then aggregated transmissions between each pair of actors' jurisdictions. Specifically, for every dyad of actors i,j, and for each risk interdependence archetype, we measured the average total yearly area burned on actor i's jurisdiction from wildfires ignited on actor j's jurisdiction.

Combining the risk mitigation coordination and fire transmission networks resulted in a multiplex network that included layers of social and ecological linkages among actors (through their jurisdictions). The social and ecological layers of this network can be visualized separately

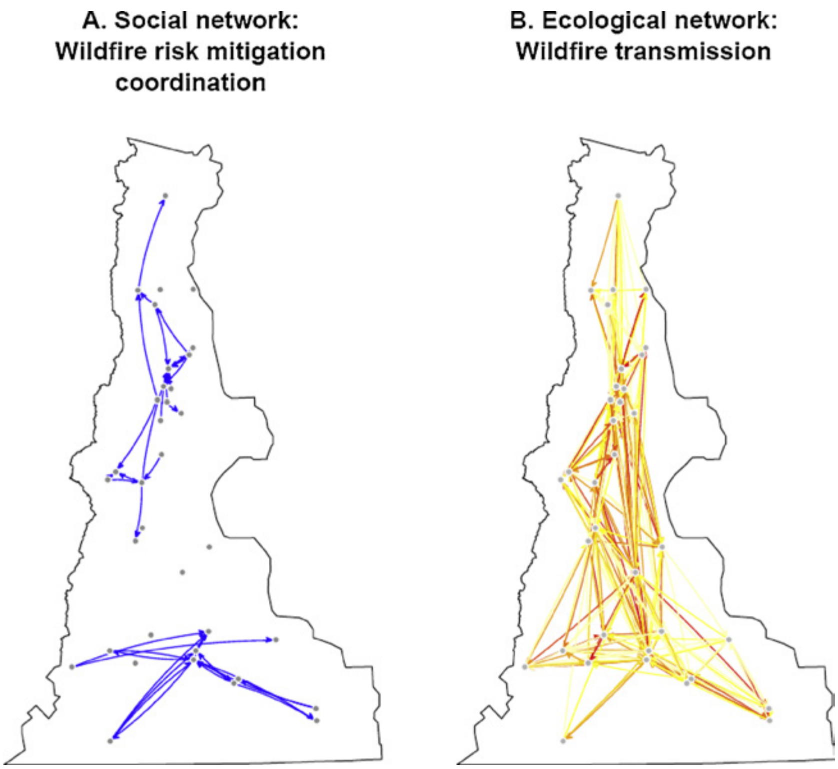


Fig. 3. Social and ecological networks. Panel A depicts patterns of coordination of wildfire risk mitigation among the 36 organizations that manage forests and wildfire conditions in the study system. Panel B depicts transmission of wildfires among the 36 organizations' jurisdictions. In Panel B, greater intensity of wildfire transmission is indicated by darker red lines. To reduce complexity, each organization's node is located at the centroid of its jurisdiction. The black outline indicates the boundary of the Eastern Cascades Ecoregion. Figures were generated using the "rgdal" package (Keitt, 2010) and the "statnet" suite of packages (Handcock et al., 2008) in the R programming environment (R Core Team, 2016). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

(Fig. 3). The social network included 40 linkages representing wildfire risk mitigation coordination. A number of actors had no coordination ties to other actors. Another notable feature of the social network is the lack of coordination linkages that span sub-regions of the study system. The tendency for actors to prefer more proximate partners has been highlighted as a key policy challenge in prior research on large-scale wildfire risk governance networks (Fischer and Jasny, 2017). The wildfire transmission network (Fig. 3B) featured some level of at least one form of risk interdependence among 40.3% of all pairs of actors. However, in comparison to the social networks, in which ties were either present or absent, in the wildfire network, relationships ranged from no burnt area to 83.3 ha burnt per year, resulting from the transmission of wildfires from one jurisdiction to another.

3.3. Exponential random graph models

We estimated an exponential random graph model (ERGM) to evaluate the likelihood that an actor coordinates with another actor as a function of a set of parameters that included actor-level attributes (e.g., size of an actor's jurisdiction), attributes of pairs of actors (e.g., whether they share the same goals), and characteristics of the way the actors are embedded in the broader network (e.g., whether actors coordinate with pairs of actors that coordinate with one another). An ERGM assesses the degree to which each parameter is over- or under-represented in the observed network relative to what should be expected by chance, as indicated by positive or negative parameter estimates, respectively. Specifically, an ERGM uses Markov chain Monte Carlo simulation to identify estimates capable of generating networks with approximately the same counts of statistics for each parameter as in the observed network (Lusher et al., 2012; Robins et al., 2007). The statistics drawn from distributions of networks simulated using parameter estimates are then used to measure standard errors associated with each parameter, and the significance of each parameter is calculated as the ratio of its estimate to its standard error. As we describe below, the ERGM we estimated included a set of parameters that allowed us to measure how the likelihood that a given actor coordinates risk mitigation activities with another actor varies as a function of exposure to the different archetypes of risk interdependence depicted in Fig. 2, while controlling for other factors that could also affect coordination.

3.4. Model parameters for risk interdependence archetypes and control variables

Our key parameters of interest were the four risk interdependence archetypes. Each archetype was operationalized as a 36*36 matrix in which the value of each cell *i,j* corresponded to the proportion of actor *i*'s total area burned annually by fires that ignited on lands managed (at least in part) by actor *j*. For example, in each cell of the matrix for archetype A (Fig. 2A), values indicated the size of burned area within lands jointly managed by actors *i* and *j* from fires that ignited with lands jointly managed by actors *i* and *j*, divided by the total area of actor *i*'s jurisdiction. This normalization (area burned / total area) was necessary to account for the relative magnitude of a given size of burned area, due to high variance in the sizes of actors' jurisdictions. Because we treated wildfire transmission as a fixed (exogenous) feature of a multiplex social-ecological network, we modeled each risk interdependence archetype as an edge covariate (Fig. 4), specified using the "edgecov" parameter in the "statnet" suite of packages (Handcock et al., 2008) in the R programming environment (R Core Team, 2016).

We included a variety of control parameters, including the proportion of actor *i*'s total area shared with actor *j*, the shortest distance

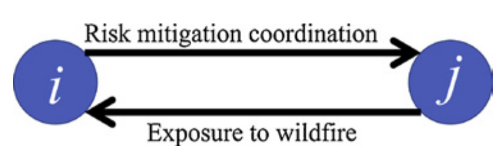


Fig. 4. ERGM parameter used to evaluate the effect of each risk interdependence archetype on the likelihood of coordination. For a pair of actors *i,j*, each parameter measured the proportion of actor *i*'s total area burned annually by fires that ignited on lands managed (at least in part) by actor *j* via a particular form of risk interdependence. For example, the parameter for archetype A measured exposure to wildfire that both ignited and burned on lands managed jointly by actors *i* and *j*.

between actors' jurisdictions, jurisdiction size, proportion of "self-burning" to total area burned, actor goals, goal homophily, and several network structural parameters. Although estimates for these parameters indicate the likelihood of coordination between pairs of actors, rather than the likelihood of coordination conditional on risk interdependence archetypes (i.e., social-ecological alignment), their inclusion served to distinguish the effects of risk interdependence from potential confounding effects such as spatial proximity, as well as to control for overall network structural characteristics. All control parameters are described in detail in Supporting file A. We conducted all network analysis using the "statnet" suite of packages (Handcock et al., 2008) in R (R Core Team, 2016). Models converged well, and we provide evidence of goodness of fit in Supporting file B.

4. Results

4.1. Risk interdependence archetypes

Although risk interdependence involves a relationship between pairs of actors, to evaluate the distribution of exposure to each archetype of risk interdependence at the actor-level, for each of the 36 actors we summed the total area of the actor's jurisdiction burned annually from all fires (i.e., from lands managed by all other actors) that corresponded to each archetype (Fig. 5). For example, if 10 ha/year of an actor's jurisdiction burned from fires that ignited on lands managed jointly with other actors, and those actors' jurisdictions did not overlap with the 10 ha burned, the actor would be exposed to 10 ha/year for archetype C (Fig. 2C). Organizations with the largest jurisdictions were predominantly exposed to risk interdependence in which wildfires both ignited and burned on jointly managed lands (i.e., archetype A, Fig. 2A). Organizations managing smaller jurisdictions tended to be more exposed to wildfire that ignited on land they did not jointly manage with other organizations (i.e., archetypes B and D, Fig. 2B and D).

4.2. Model results

The first four parameter coefficients estimated in the ERGM indicate the likelihood that a given actor coordinates risk mitigation activities with another actor as a function of risk interdependence (Table 1). The significant negative estimate for the effect of risk interdependence archetype A indicates that the likelihood that an actor *i* coordinates with an actor *j* declines as a function of actor *i*'s exposure to fires that ignite and burn within land jointly managed by both actors *i* and *j*, counter to our first hypothesis.

The next three parameter estimates provide support for our remaining hypotheses. Specifically, the likelihood of coordination (*i* to *j*) increases as a function of *i*'s exposure to fires that ignite within land within actor *j*'s jurisdiction and burn within land jointly managed by both actors *i* and *j* (H2, Fig. 2B), as well as fires that ignite within land jointly managed by both actors *i* and *j* and burn within land managed by actor *i* (H3, Fig. 2C), and fires that ignite on land managed by actor *j* and burn within land managed by actor *i* (H4, Fig. 2D).

Although estimates for the remaining parameters relate to the likelihood of coordination between pairs of actors, rather than the likelihood of coordination conditional on risk interdependence, they nevertheless shed light on other key factors that shape social interaction among actors concerned with wildfire risk. In particular, coefficients for "Percent shared area" and "Distance (Km)" indicate that the extent to which actors' jurisdiction overlap as well as the spatial proximity of these jurisdictions increase the likelihood of coordination. Actors are more likely to coordinate with other actors that share the same goal

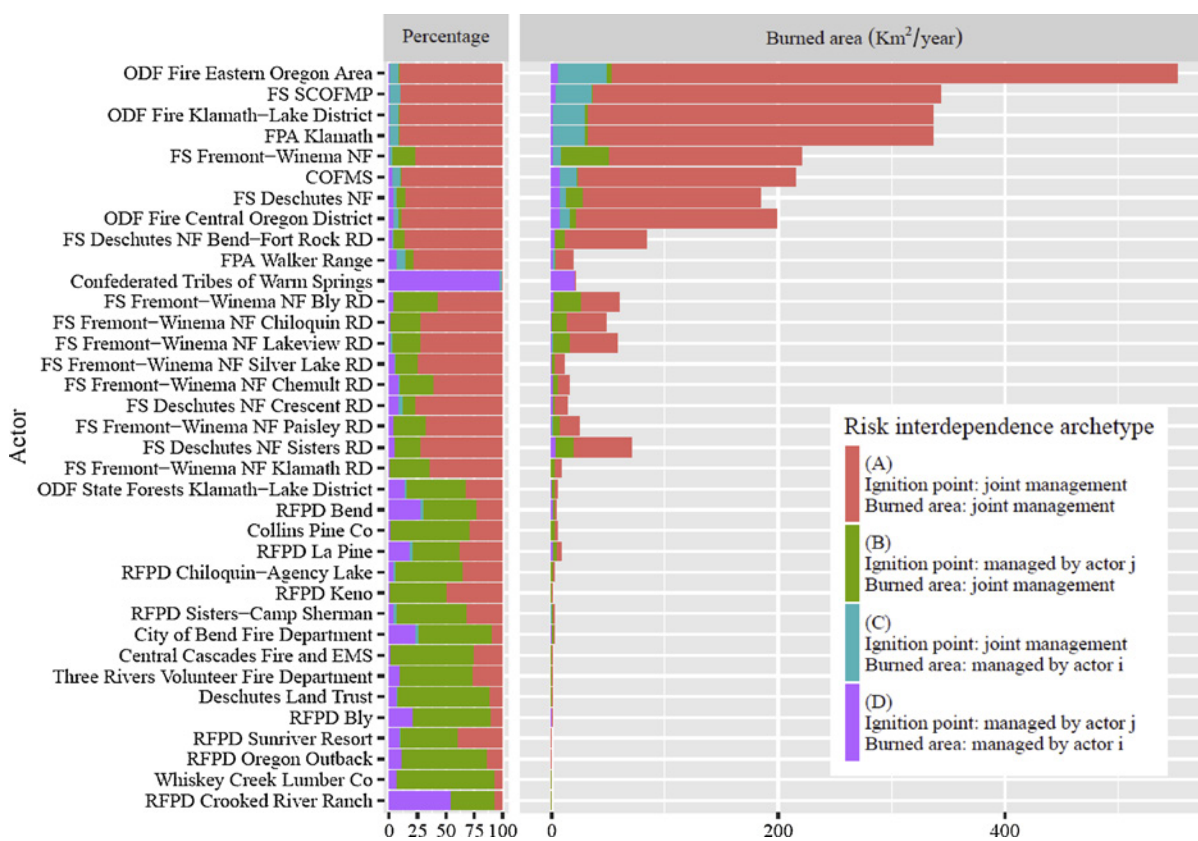
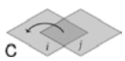


Fig. 5. Degree to which each organization is affected by each of the risk interdependence archetypes. ODF = Oregon Department of Forestry; SCOFMP = South Central Oregon Fire Management Partnership; FPA = Forest Protective Association; FS = Forest Service; COFMS = Central Oregon Fire Management Service; NF = National Forest; RD = Ranger District; RFPD = Rural Fire Protection District.

Table 1
ERGM results.

Parameter		Estimate (Standard error)
	Ignition point: joint management Burned area: joint management	−0.04 (0.02)*
	Ignition point: managed by actor *j* Burned area: joint management	0.02 (0.01)†
	Ignition point: joint management Burned area: managed by actor *i*	0.64 (0.18)***
	Ignition point: managed by actor *j* Burned area: managed by actor *i*	0.05 (0.02)*
Percent shared area		0.03 (0.01)***
Distance (Km)		−0.03 (0.01)*
Size of jurisdiction (Km^2/100)		−0.01 (0.00)**
Percent of jurisdiction burnt		−0.11 (0.34)
Percent of jurisdiction self-burnt		1.56 (0.71)*
Goal = forest restoration[1]		−0.18 (0.23)
Goal homophily		1.25 (0.41)**
Dropped pendants		0.08 (0.04)†
Edges		−5.54 (1.32)***
Reciprocity		1.22 (0.64)†
GW out-degree ($\theta_S = 0.8$)		−1.28 (0.70)†
GW in-degree ($\theta_S = 0.8$)		−0.06 (0.75)
GW edgewise shared partners ($\theta_T = 0.5$)		0.29 (0.30)
AIC		264.54
BIC		351.91
Log Likelihood		−115.27

Notes:
[1]Reference category: fire protection.
Significance code: *** p-Value < 0.001; ** p-Value < 0.01; * p-Value < 0.05; † p-Value < 0.1.

(either fire protection or forest restoration), as indicated by the "Goal homophily" parameter estimate. The "Reciprocity" coefficient indicates that coordination tends to be bi-directional (i.e., given that *j* coordinates with *i*, it is more likely that *i* coordinates with *j*). The remaining parameters are described and interpreted in Supporting file A.

5. Discussion

Our findings indicate that landscape-level patterns of wildfire transmission predict patterns of risk mitigation coordination among actors managing lands within that landscape. Among pairs of actors in which at least one is exposed to wildfire that spreads from lands at least partly managed by the other, we find significant relationships between the scope of exposure and the likelihood of coordination that cannot be explained just by the well-documented (and in our case, significant) effects of shared management goals and geographic proximity alone (Fischer and Jasny, 2017).

Of the four archetypes of risk interdependence we examine, three had a positive effect on risk mitigation coordination, while the other had a negative effect. Although our cross-sectional data do not allow us to draw causal inferences, our findings are in agreement with our expectation that actors may choose partners in order to influence their land management practices, and are consistent with evidence that social selection and social influence are dynamically coupled in environmental governance networks (Barnes et al., 2016; Berardo, 2013). In particular, actors exposed to risk via archetypes B and D (which both had a positive and significant effect on coordination) do not jointly manage ignition-prone lands with prospective partners. Although at-risk actors may not be able to directly shape forest management activities on these lands, they may yet influence management decisions by establishing relationships with actors that do manage them.

Additionally, the positive and significant effects of archetypes C and D suggest that actors choose partners based on their own scope of risk exposure relative to their partners. Stated another way, because joint management distributes responsibility for wildfire response (Canadas et al., 2016), when actors bear greater responsibility for protecting values at risk from wildfire, the stakes of exposure to wildfire (and correspondingly, the benefits of risk mitigation) are higher. Therefore, actors may be especially inclined to form partnerships that help reduce wildfire exposure on lands they manage independently from their partners.

Our findings also suggest that the dynamics of risk exposure necessitate a more nuanced understanding of the relationship between spatial proximity and partner selection. In particular, the negative and significant effect of archetype A (in which an actor and its prospective partner jointly manage lands within which fires can both ignite and burn) was contrary to our H1. This result is surprising in light of extensive research showing that coordination is more likely among actors exposed to a common source of risk (Canadas et al., 2016; Fischer and Charnley, 2012; Fleeger, 2008; Meadows et al., 2013). H1 was also consistent with expectations that proximity would lower the transaction costs associated with risk mitigation coordination. Transaction costs refer to costs incurred while reaching agreements, as well as monitoring and possibly enforcing the implementation of those agreements (Coase, 1960; North, 1990; Williamson, 1981), and research on inter-organizational governance networks highlights their importance in shaping interaction among actors (Berardo and Lubell, 2016; Feiock, 2007; Lubell et al., 2002). However, transaction costs may still be high among actors jointly managing land. In particular, in many cases a pair of actors whose jurisdictions overlap have distinct management responsibilities, and as a result may have different values and goals for addressing hazard conditions. For example, one actor may prefer to suppress all wildfires to protect timber or scenic values while another land manager may seek to mimic natural ecological disturbance process by carrying out prescribed burns or allowing lightning-ignited fires to burn understory vegetation (Charnley et al., 2017; Fischer and Charnley, 2012). If such trade-offs between values result in antagonistic relationships among organizations, coordination may be less likely despite numerous opportunities to interact. Moreover, the value of partnerships based on archetype A may be outmatched by the value of a partnership based on archetype C, which provides the same opportunities to jointly address the source of exposure on ignition-prone lands, as well as the added benefit of reducing exposure to lands managed independently of the prospective partner. Under these conditions, actors may prioritize partnerships that reduce their exposure to wildfire on lands for which they are solely responsible (archetype C) over lands in which the partner shares responsibility (archetype A). After all, actors have limited capacity for social interaction, and may strategically prioritize interactions that offer the greatest potential payoff (Lubell, 2013; Scott and Thomas, 2015).

Taken together, these results have important implications for wildfire risk governance in the Eastern Cascades Ecoregion (ECE). In particular, while social-ecological alignment was more likely for three of the four risk interdependence archetypes, the archetype that had a negative effect on coordination was also the dominant form of risk exposure among actors managing large jurisdictions (Fig. 4). Although actors readily contribute to social-ecological alignment in certain situations, these situations only encompass a modest percentage of their aggregate exposure to risk from wildfires. This highlights both a positive and negative aspect of self-organizing environmental governance networks – localized processes of social selection may enhance certain forms of social-ecological alignment (e.g., in response to risk exposure via archetypes B, C, and D), but because actors do not intentionally seek to enhance alignment, these positive effects may be outweighed by misalignment (e.g., aversion to coordination in response to archetype A) that plays out at large spatial scales. Abundant research highlights the fact that large-scale wildfire risk governance is necessary but not happening (Fischer et al., 2016; North et al., 2015), and our study suggests that a potential reason may be because actors prioritize partnerships that primarily contribute to social-ecological alignment in more localized settings, rather than at large spatial scales. In this respect, our research also reveals opportunities to improve regional wildfire risk governance by incentivizing interaction among pairs of organizations that jointly manage large wildfire-prone forested areas, which typically include federal/state agencies as one or both parties. In particular, these situations highlight the potential role for state and federal agencies to act as "risk mediators" by exercising leadership and incurring transaction costs in order to facilitate—among other actors—the types of relationships conducive to the performance of the governance system as a whole (McAllister et al., 2015). Such an approach would be consistent with the U.S. National Cohesive Wildland Fire Management Strategy, which provides resources as well as institutional support for agencies to coordinate fuels reduction as well as wildfire response with diverse stakeholder groups, including other agencies (Calkin et al., 2011).

This study is relevant to the management of other natural hazards besides wildfire as well as in other environmental governance contexts in which desirable outcomes hinge upon reducing ecological connectivity (e.g., management of invasive species; Lubell et al., 2017) or enhancing it (e.g, enabling species dispersal among remnant habitat patches; Bergsten et al., 2014). For example, our finding that actors interact in ways that promote relatively localized social-ecological alignment at the expense of alignment over large spatial scales, where they are less responsible for outcomes, may help explain observations that alignment is less common at higher spatial scales (Bergsten et al., 2014; Ernstson et al., 2010; Guerrero et al., 2015a). Additionally, our analysis demonstrates the value of risk interdependence archetypes in decomposing complex spatial configurations characteristic of social-ecological networks in which organizations' or institutions' spheres of influence overlap. This complexity is not unique to our study system, but characterizes all social-ecological systems in which formal authority is fragmented (Berardo and Scholz, 2010), or where institutional arrangements such as co-management explicitly create interdependence among actors that share decision-making responsibilities within a single administrative jurisdiction (Armitage et al., 2008).

6. Conclusion

While a growing body of empirical evidence supports the core idea that successful environmental governance outcomes depend on the alignment of social and ecological processes (Bodin et al., 2014; Bodin and Tengö, 2012; Epstein et al., 2015; Guerrero et al., 2015b; Sayles and Baggio, 2017; Young, 2002), the factors that facilitate or constrain alignment have received limited attention. In this paper, we show that social-ecological alignment can sometimes, but not always, develop as a by-product of social selection. Our overarching finding—that the likelihood of coordination among actors depends upon spatial configurations of their wildfire risk interdependence—contributes to our theoretical understanding of how environmental governance systems self-organize via strategic partner selection (Berardo and Scholz, 2010). Specifically, we find that actors select partners in ways that contribute to social-ecological alignment when they are exposed to risk from fires that ignite on lands that they do not manage (thereby providing opportunities to indirectly reduce hazardous conditions where fires originate) as well as from fires that burn on lands managed independently of partners (where the benefits of risk mitigation are greater because responsibility is not shared). However, we find that actors tend to avoid partnerships that would contribute to the form of social-ecological alignment that could address the majority of risk to which actors are collectively exposed, which highlights the limitations of relying upon "localized" processes by which actors strategically select partners in regional risk governance systems.

Methodologically and conceptually, our "risk interdependence archetypes" provide an approach for analyzing social-ecological systems in which patterns of ecological connectivity have the potential to transmit risk across actors' jurisdictions, which may overlap. These archetypes build upon the sets of social-ecological network configurations developed by Bodin and colleagues (Bodin et al., 2016, 2014; Bodin and Tengö, 2012), but place greater emphasis on the nature of ecological relationships, primarily by using continuous rather than binary measures of ecological connectivity (Ager et al., 2017, 2012). This approach requires controlling for numerous spatial variables (e.g., size of actor jurisdiction, distance between actors) which are not typically included in analyses of social-ecological networks, despite their potentially important roles in explaining social and/or ecological connectivity (Epstein et al., 2015; Lubell et al., 2017). Our experience suggests that conceptualizing such systems as multiplex networks can offer significant opportunities to account for ecological patterns and processes over multilevel (or multi-mode) analysis. In particular, because a multiplex social-ecological network can capture ecological processes that link social nodes (e.g., fire transmission between jurisdictions), this approach is well-suited for analysis of systems that lack discrete ecological nodes such as vernal pools, mountaintops, lakes, or isolated protected areas.

The present study offers a foundation for important future work on the structure and function of different configurations of social-ecological networks. In particular, while we investigated the relationship between patterns of risk interdependence and social selection, future research examining how risk interdependence shapes social influence (e.g., the diffusion of innovative wildfire risk mitigation practices through the actor network) could improve our understanding of how social networks shape the land use practices implemented by actors, which in turn affect environmental conditions and the transmission of risk across the landscape.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.gloenvcha.2018.11.007.

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