



Research, part of a Special Feature on [Adaptation in Fire-Prone Landscapes: Interactions of Policies, Management, Wildfire, and Social Networks in Oregon, USA](#)

Historical perspective on the influence of wildfire policy, law, and informal institutions on management and forest resilience in a multiownership, frequent-fire, coupled human and natural system in Oregon, USA

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ABSTRACT. We examine the influence of wildfire institutions on management and forest resilience over time, drawing on research from a multiownership, frequent-fire, coupled human and natural system (CHANS) in the eastern Cascades of Oregon, USA. We constructed social-ecological histories of the study area's three main landowner groups (national forest, private corporate, and tribal) using a historical framework (1905–2010). Our findings highlight two infrequently recognized linkages of multiownership, frequent-fire CHANS: (1) informal institutions (e.g., cultural norms, knowledge system and fire paradigm) and institutional history often influence wildfire management adaptation (changes in forest fuel treatment, harvest fuel treatment, and wildfire incident response) through interactions with formal institutions (e.g., policy, law) and consequent effects on managers' decision-making flexibility; (2) institutional interactions over time can influence forest resilience, thereby contributing to forest structural variation in multiownership landscapes. Consequently, the factors that contribute to maladaptive wildfire management are heterogeneously distributed across ownerships and the landscape. The timing of institutional dynamics also matters: manager flexibility to respond adaptively to wildfire hazard change seems to depend on synchronicity in evolution between informal and formal institutions, whereas asynchronous evolution (e.g., policy change, coupled with delayed shift in cultural norms or fire paradigms) may generate a time lag between unanticipated ecological feedbacks and management response. Thus, interventions that promote informal institutional evolution in tandem with developments in policy and law may shorten time lags, accelerating adaptation. A historical perspective can facilitate broad-scale, adaptive responses to wildfire-related ecological feedbacks in several ways: by providing insight into how informal institutions and institutional history interact with formal institutions to influence wildfire management behavior; by providing a historical baseline and system stages that contextualize current management behavior, ecological conditions, and policy options; and by illuminating historical sources of variation among ownerships and how they might be addressed.

Key Words: *coupled human and natural system, environmental history, institutions, multiownership landscape, tribal forests, wildfire management*

INTRODUCTION

Fire is a fundamental ecological process that maintains diverse ecosystem services and social values in communities around the world (Noss et al. 2006). In recent years, however, managing wildfire risk in human-settled, fire-prone, forested landscapes has become a nearly intractable problem in the U.S. West and globally. On the one hand, decision makers face agency mandates to control immediate wildfire risk to property and lives, which has generally led them to suppress fire incidents; on the other, fire suppression driven fuel accumulation has increased wildfire hazard, incident management costs, and loss (the “wildfire paradox,” Calkin et al. 2014; or “socioecological pathology,” Fischer et al. 2016). Ecological resilience to wildfire, i.e., the capacity to experience shocks yet retain essentially the same function, structure, feedbacks, and therefore, identity (Gunderson 2000, Walker et al. 2004), appears to be declining in frequent-fire ecosystems (Díaz-Delgado et al. 2002, Savage and Mast 2005, Chapin et al. 2010). In the western United States, wildfires are becoming more severe, as measured by tree mortality (Westerling et al. 2006, Stephens et al. 2013). Forest fuel treatments have disproportionately treated the wildland urban interface (WUI), thereby limiting restoration of the broader wildland area (Schoennagel et al. 2009) where ecosystem services and timber are at stake. In the WUI, homes and other structures are also at stake, as is human health, and safety of fire fighters and residents (McCaffrey and Olson 2012). Furthermore, fire suppression costs are increasing and

unsustainable. Suppression consumed > USD \$1 billion/yr of U. S. land management agency budgets in 11 of 14 years (2000–2014) and then exceeded \$2 billion in 2015 (Whitlock 2004, USDI-NIFC 2016), limiting agency capacity to fulfill its range of policy and legal mandates (Stephens and Ruth 2005, USDA-FS 2015).

The goals of our study are to generate historical insights that explain how the wildfire paradox developed in one multiownership landscape, to expand the understanding of influences (including constraints) on management evolution and adaptation (vs. stasis), and ultimately, to increase coordination of broad-scale wildfire management. We also aim to account for variation in wildfire management and forest resilience among ownership groups. Our focus is on the social subsystem of a frequent-fire coupled human and natural system (CHANS; Liu et al. 2007). We are particularly interested in the influence of less well-recognized institutional factors (informal institutions, institutional history) on management behavior and, in turn, forest resilience.

We pose three research questions related to these goals and address them in a multiownership, frequent-fire system in the eastern Cascades of Oregon, USA. (1) How has wildfire management behavior evolved (changes in forest fuel treatment, harvest fuel treatment, and wildfire incident response) since the beginning of professional forest management (1905–2010) and varied among large landowner groups? (2) How has the evolution

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(or stasis) of formal and informal institutions, and interactions between them, related to the evolution (or stasis) of wildfire management behavior over time in different large landowner groups and varied among landowner groups? (3) Does variation in the evolution of wildfire management institutions and behavior among landowner groups contribute to variation in wildfire-resilient forest structure?

We explore these questions using a CHANS-historical framework and a CHANS conceptual model (described below). In doing so, we show that this combination of heuristics can illuminate several important, incompletely understood aspects of multiownership, frequent-fire, forest systems: social heterogeneity, social subsystem interactions (institution-behavior linkages), and social-ecological linkages over time (Spies et al. 2014). The historical framework assists our effort to trace how social subsystem elements (institutions, behaviors) have evolved (or remained static) over time, and the effects of this evolution on current wildfire-resilient forest structure. Our application of this framework to a set of distinct ownership groups that compose a multiownership landscape addresses the need for broad-scale, cohesive management of wildfire and other disturbances across land ownerships, given that such ecological processes transcend administrative boundaries (Knight and Landres 1998, Spies et al. 2007). Only a few historical studies of forest management have investigated multiownership landscapes (e.g., Steen-Adams et al. 2011).

We argue that in the eastern Cascades system, wildfire management adaptation (changes in forest fuel treatment, harvest fuel treatment, and wildfire incident response) was influenced by the interaction of informal institutions (cultural norms, knowledge system and fire paradigm) and institutional history with formal institutions (policy, law; following Folke et al. 1998, Petty et al. 2015) because of effects on decision-making flexibility in responding to ecological feedbacks. We also argue that institutional interactions play a role in wildfire-resilient forest structure, which we expected to vary by ownership owing to institutional variation. Institutional interactions over time thus may influence CHANS properties of sensitivity and responsiveness to ecological feedbacks. A forest management application is that recognizing the array of institutional factors (formal vs. informal institutions, institutional history) as potential influences on wildfire management may assist efforts to stabilize unanticipated ecological feedbacks (e.g., wildfire hazard increase driven by management stasis).

Social science has expanded knowledge of the human dimensions of wildfire management in response to growing settlement in frequent-fire landscapes (McCaffrey and Olsen 2012, McCaffrey et al. 2013). An important research area is the influence of institutions (e.g., policy) and associated processes (policy evolution) on wildfire management flexibility and behavior (Busenburg 2004, Stephens and Ruth 2005, Steelman and Burke 2007, McCaffrey et al. 2013). Institutions are the systems of established and prevalent social rules that structure human decision making and behavior within social groups and in relation to the natural world (Ostrom 1990, North 1990, Crawford and Ostrom 1995, Helmke and Levitsky 2004, Hodgson 2006). Formal institutions (e.g., laws, policies, constitutions) are constructed within officially sanctioned channels. Informal institutions have

been defined as “socially shared norms, usually unwritten, that are created, communicated, and enforced outside of officially sanctioned channels” (Helmke and Levitsky 2004:727). Examples include cultural norms and knowledge systems (Crawford and Ostrom 1995, Coughlan and Petty 2012). By contrast, organizations are groups of people who work together in a formal structure to pursue mutually held objectives (e.g., the U.S. Forest Service). Institutions, both formal and informal, are embedded within such organizations. Management goals are related to institutions as drivers of management behavior. However, there are important differences between these concepts: in the proximate term, goals drive behavior, as is often consistent with the structure of forest management plans. In the longer term, management goals are embedded in a society’s culture (values and beliefs), policies, laws, and other institutional factors. Here, our focus is on these enduring, underlying factors.

Institutions merit research attention because they set sideboards on viable responses to ecological feedbacks such as fuel accumulation (Gunderson et al. 1995, Folke et al. 1998, Gunderson and Holling 2002, Walker et al. 2006). Institutions are not frozen in time (Davidson-Hunt and Berkes 2003); rather, they evolve through social processes of learning and adaptation, which can expand social-ecological resilience. The management and ecological effects of formal and informal institutional interactions over time (e.g., when a new policy is promulgated but cultural norms or fire paradigms remain static) are poorly understood. Formal institutions such as policy direct management behavior and are well recognized (Garmestani et al. 2013). However, lesser-understood informal institutions also influence behavior (Helmke and Levitsky 2004, Bratton 2007). For instance, “entrenched disincentives” of U.S. land management agencies can constrain managers’ flexibility to respond to wildfire incidents (North et al. 2015). Informal norms may interfere with the signaling of an environmental hazard or constrain managers’ flexibility to implement wildfire policy fully. Conversely, some informal institutions (e.g., strategies of community-engaged management, traditional ecological knowledge) may increase sensitivity to environmental feedbacks (Berkes et al. 2000, Olsson and Folke 2001). Either way, informal and formal institutions may interact to direct behavior in ways that are more complex and less predictable than the specified directives of policy and law alone.

The main fields that have expanded the understanding of society-fire interactions over time are environmental history, historical ecology, and pyrogeography. Environmental history approaches tend to focus on the politico-economic, cultural, and ecological influences on human-nature interactions over time, and how past circumstances and human agency shape current outcomes (e.g., Langston 1995, Pyne 1997, Rothman 2007). By comparison, historical ecology approaches mainly examine long-term change in forest landscape structure and processes (e.g., stand density, fire regimes) resulting from the interaction of biophysical and social factors, including institutions, knowledge systems, and social systems of production and distribution (Coughlan and Petty 2012, Petty et al. 2015). Key insights are that behavioral rules (institutions) are socially constructed through the accumulation of norms and knowledge, and that institutions are contingent on historical, cultural, and ecological context. Pyrogeography also employs an evolutionary approach. A core

theory is that humans have coevolved with fire regimes. Thus, social structures (organizations, technology) to manage fire have evolved over time and vary geographically (Bowman et al. 2011).

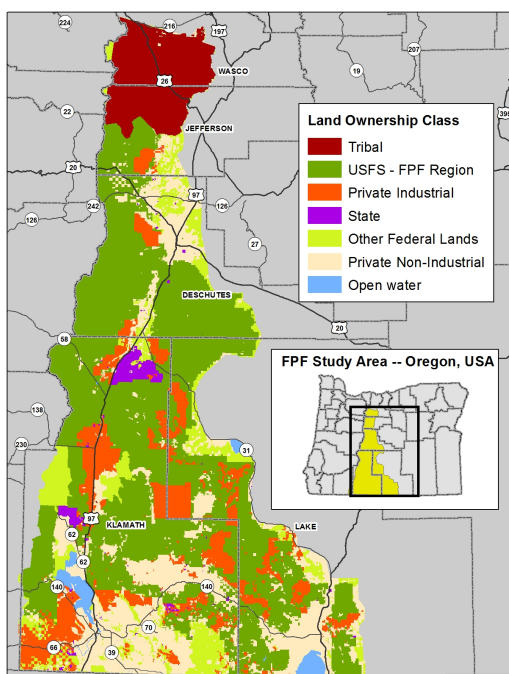
Few investigators have examined influences on wildfire management decision making and behavior using a CHANS approach (although see Spies et al. 2014). A CHANS approach examines processes that link human and natural subsystems, similar to a social-ecological systems approach (e.g., Berkes et al. 2000, Walker et al. 2006). A distinctive aspect of CHANS analysis is a focus on feedbacks and emergent system properties such as resilience (Liu et al. 2007), which corresponds with our study approach. We examine how social-ecological feedbacks (management response to wildfire hazard) and processes (institutional evolution) develop over time. We anticipate that our examination of long-term social-ecological interactions and attention to historical context will expand knowledge of how the wildfire paradox developed in this Oregon system and suggest insights to improve broad-scale wildfire management across ownerships.

METHODS

Study area

The study area is located in the eastern Cascades of Oregon (Fig. 1). The area includes portions of five counties and covers approximately 3,270,000 ha. Three frequent-fire forest types, i.e., moist mixed conifer, dry mixed conifer, and ponderosa pine, comprise the main potential vegetation types (Merschel et al. 2014, Stine et al. 2014). Ecological composition varies with steep elevational, moisture, and temperature gradients, as well as soil type, geomorphology, and disturbance history, which includes fire history, volcanism, and glaciation (Perry et al. 2011).

Fig. 1. Land ownership pattern (2010) of study area in east Cascades Oregon, USA.



The large landowners who are the focus of our study are the U. S. Forest Service (USFS), private corporate forest owners, and American Indian tribes, currently owning 48%, 12%, and 8% of the study area, respectively. There are two national forests in the study area, the Deschutes National Forest (DNF) and the Fremont-Winema National Forest (FWNF). The DNF and Fremont National Forest (FNF) were established in 1908. The Winema National Forest was created in 1961 from former Klamath Tribal reservation land and adjacent national forests. The Fremont and Winema National Forests were administratively combined in 2002. Historically, private industrial timber companies, including Shevlin-Hixon, Brooks-Scanlon, Gilchrist, and Weyerhaeuser, owned a substantial proportion of the study area. In the 1990s, several large companies left the region, selling their lands to Timber Investment Management Organizations or Real Estate Investment Trusts (Kelly 2010). At the time of our research, five private corporate actors each owned at least 10,000 ha of study area land. We report the current management behavior and forest structure of these five private owners combined, despite substantial within-ownership variation, because of our main focus on cross-ownership group variation and practical limits on data collection. For results highlighting within-ownership variation of this ownership group, see Charnley et al. (2017). The study area also historically included two tribal reservations: the Klamath and the Warm Springs. The Klamath Tribes lost federal recognition and their reservation lands in 1954 under the *Klamath Termination Act* (<http://klamathtribes.org/history/>). They regained federal recognition, but not their lands, in 1986. Today, these lands are part of the FWNF and private corporate ownerships. We restrict the tribal ownership category to the Warm Springs Reservation (WSR) because significant differences in the management histories of the two reservations make generalization across administrative units unsound. The WSR was created in 1855 and is home to three tribes that historically inhabited the Columbia Plateau: the Warm Springs, Wasco, and Paiute (Aguilar 2005). For most of the study period (1905–1992), “tribal forest managers” refers to employees of the Bureau of Indian Affairs (BIA; until 1947, U.S. Indian Service), most of whom were not tribal members.

Coupled human and natural system (CHANS) historical framework and conceptual model

We developed two interrelated heuristics to address our study questions regarding the role of social subsystem evolution on wildfire management and forest resilience: a CHANS-historical framework (Table 1) and a CHANS conceptual model (Fig. 2). Historical frameworks divide the continuum of management history into discrete, coherent periods through a technique known as periodization (e.g., Steen-Adams et al. 2015). Such devices can help investigators systematically trace how phenomena such as current wildfire management institutions and behaviors have evolved over time. Use of historical frameworks by researchers has expanded knowledge of social influences on fire regimes and fire landscapes and highlighted strategies for coexistence between societies and wildfire (e.g., Pyne 2009, Bowman et al. 2011).

Our CHANS-historical framework has its origins in our review of the environmental history literature, particularly of U.S. land management agencies (Hirt 1994, Langston 1995, Pyne 1997, 2009, Robbins 1997, Rothman 2007, Hays 2009, Williams 2009, Bramwell 2013). After developing the initial framework, we

Table 1. Coupled human and natural system-historical framework of wildfire management in frequent-fire forest among large forest ownerships.

Historical framework stage	Description	Stage start and end dates		
		U.S. Forest Service	Private corporate group	Tribal group
Stage I: establishment	Establishment of initial wildfire and forest management laws and policies and organizational structure	1905–1924 [†]	1911–1924 [‡]	1910–1924 [§]
Stage II: systemization-centralization	Period during which wildfire and forest laws and policies were designed to fulfill management objectives through a systematic, centralized organizational structure and procedures	1924–1970s	1924–1997 [¶]	1924–1975 [#]
Stage III: reevaluation	Reevaluation of wildfire and forest management objectives and dominant knowledge system, leading to wildfire laws and policies that allow decision maker flexibility to pivot away from wildfire practices of stage II and tending to rescind laws and policies of stage II	1970s–1995 ^{††}	1997–present ^{‡‡}	1975–1995 ^{§§}
Stage IV: redirection-reorganization	Period during which laws and policies explicitly direct managers to pivot wildfire practices away from those of stage II and to adopt new practices, generally within a reorganized organizational structure	1995–present	–	1995–present ^{¶¶}

[†]1905: *Transfer Act* of 1905.

[‡]1911: First Oregon Forest Fire Law and date of organic act of Oregon Department of Forestry (initially Forestry Branch of Oregon) and of Forest Protection Association administrative system in response to federal-level *Weeks Act*.

[§]1910: Establishment of Forestry Branch of the Bureau of Indian Affairs via the *Indian Omnibus Act* of 1910.

^{||}1924: *Clarke-McNary Act*.

[¶]1924: *Clarke-McNary Act*, a federal-level act that triggered expanded state-level laws (e.g., Oregon Forest Fire Laws [1925, 1937, 1947, 1954] and U.S. Forest Service-state-private corporate fire suppression cooperation; 1941: *Oregon Forest Conservation Act*.

[#]1924: *Clarke-McNary Act* established a cooperation model, which carried over to U.S. Forest Service-tribal manager cooperation; 1934: *Wheeler-Howard [Indian Reorganization] Act*, which directed sustained yield forestry.

^{††}1978: Rescindment of *Clarke-McNary Act* amendments and of 10:00 A.M. policy via National Forest Manual revisions.

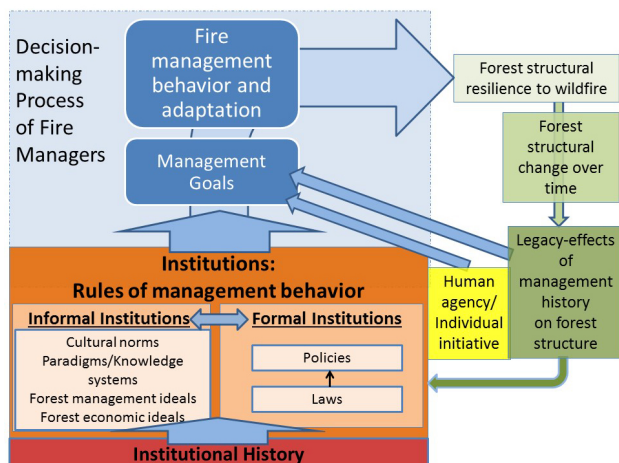
^{‡‡}1997: *Oregon Forestland-Urban Interface Fire Protective Act* (Senate Bill 360); 2009: Oregon Revised Statute 477.005, Forest Protection of Forests and Vegetation; 2014: ODF Regional Solutions Participation Plan, which includes forest fuel treatment as a Fire Program area.

^{§§}1975: *Indian Self-determination and Education Assistance Act*.

^{|||}1995: Federal Wildland Fire Management Policy.

^{¶¶}1995: Federal Wildland Fire Management Plan.

Fig. 2. Conceptual model of social subsystem of fire-frequent coupled human and natural system, with focus on the array of wildfire institutional influences (formal institutions, informal institutions, institutional history) on management behavior.



identified and integrated connections to the panarchy framework, which theorizes stages of change in complex adaptive systems (Berkes et al. 2000, Gunderson and Holling 2002). Regarding historical methods, we emphasize the retrospective, not predictive, application of our framework. Thus, alternative stages and trajectories to those presented may develop in the future, due to human agency, situational circumstances, or other factors. We tailored the framework to the eastern Cascades system by reviewing secondary sources (e.g., Logan 1982, ODF-INR 2005, Hunt-Jones 2008, Thorpe 2011) and primary documents. We identified four historical stages of frequent-fire CHANS through our review of policy and legal history, consistent with the study focus on institutional drivers. The stages are: stage I, establishment; stage II, systemization-centralization; stage III, reevaluation; and stage IV, redirection-reorganization.

We applied our historical framework to the USFS, private corporate, and tribal land ownership groups. USFS history functions as the timeline's foundation owing to the agency's historical leadership of wildfire management in the U.S. West (Pyne 1997). We found that the timing of institutional and behavioral shifts varied among ownership groups, consistent with their relative independence from one another. Hence, we provide a distinct chronology of stages for each ownership group, rather than standardized dates across all ownerships (Table 1).

Table 2. Metrics of wildfire-resilient forest structure.

Metric	Variable type	Definition
Resilient forest structure [†]	Ecological state	Resilient forest, as a proportion of ownership class area: Fire-frequent potential vegetation type units (moist mixed conifer, dry mixed conifer, and ponderosa pine) having large trees and open canopy (tree size ≥ 50 cm and 10–40% canopy cover), or tree size ≥ 38 cm, with moderate canopy cover (40–60% and single canopy layer)
Early seral structure	Ecological state	Early seral forest, as a proportion of ownership class area: Land covers include grass/shrub and seedling/sapling vegetation with open and moderate forest cover, and poles 12.7–25.4 cm diameter at breast height where cover $< 10\%$
Size class	Forest structure	Size class, as a proportion of ownership class area: Size classes are < 38 cm (small), 38–50 cm (medium), > 50 cm (large and giant)
Canopy cover class	Forest structure	Canopy cover class, as a proportion of ownership class area: Cover classes are 10–40% (open), 40–60 cm (intermediate), $> 60\%$ (open)

[†]Fire-resilient structural attributes are based on historic forest conditions and fire regimes (Hagmann et al. 2014, Merschel et al. 2014).

The study period end-date is 2010, rather than the “present.” A trade-off of this history methodological decision is the exclusion of very recent (post-2010) developments from the scope of formal analysis, which is an important consideration, given the different chronologies among ownership groups (e.g., private corporate vs. USFS). In the effort to balance methodological norms with a complete presentation of fire management developments, we note emergent developments (e.g., post-2010 policies for private corporate owners) and potential implications (e.g., influences on manager behavior) in the *Discussion*.

We also developed a CHANS conceptual model. Whereas our historical framework is designed to trace institutional and management evolution systematically over the long term (1905–2010), the conceptual model supports the examination of social-ecological system components and processes. Our conceptual model builds on that of Spies et al. (2014), which portrays feedbacks among social factors, management decisions, and landscape conditions. Our model focuses on the social subsystem. We are interested in the linkages between institutions (formal, informal), landowner behavior (wildfire management), and landscape condition (wildfire-resilient forest structure). We conceptualize management goals as a system component that is shaped by institutions, as well as two factors that are generally beyond the scope of this study: ecological legacies of past management (Charnley et al. 2017) and human agency (Coughlan and Petty 2012). Key processes are institutional evolution and management decision making and adaptation, as manifested through wildfire management behavior. “Wildfire management” references three types of behavior: (1) wildfire incident response; (2) activity fuel treatment (e.g., logging debris); and (3) forest or natural fuel treatment. Two distinctive features of our model are treatment of informal vs. formal institutions as distinct system drivers and inclusion of institutional history as a behavioral influence.

Social data collection and analysis

Social data fall into four categories: (1) archival records, consisting of documents, photographs, and maps; (2) semistructured interview data; (3) agency activity data and current forest management documents; and (4) legislation and policy documents. We collected archival records from national, state, and county archives and historical societies (National Archives and Records Administration, Oregon State Archives, Deschutes County Historical Society, Forest History Society) and agency on-site collections. Collection categories include annual reports, forest

inspections, management plans, policy documents, fire science program reports, and organization records.

Interviewees were identified through interaction with lead management personnel from each ownership (e.g., natural resource program directors), who pointed us to key informants. Where appropriate, we also employed chain referral sampling (Bernard 2006). Key informants represented the three large landowner groups, including 21 USFS managers, 5 private corporate forest managers, 18 tribal managers, and 3 state-county informants. Our semistructured interview protocol focused on two topics: (1) wildfire and forest management practices, past and present; and (2) socioeconomic influences on management, particularly institutional factors. Interviews were transcribed before analysis.

We collected current management documents for the national forests and Warm Springs Indian Reservation. We also compiled activity records from the National Fire Plan Operating and Reporting System (NFPORS), which reports forest fuel reduction activities on both USFS and tribal ownerships and is considered fairly reliable for the years 2005–present. Finally, we compiled a database of land management policy and legislation from national and state archives and electronic resources.

We processed archival and interview data using historical analysis and qualitative content analysis (Smith and Kleine 1986, Berg 2004, Brundage 2013). We developed a database and used a directed approach to develop a classification scheme based on key terms of complex adaptive systems and CHANS theory, e.g., institution, adaptation, feedback (Gunderson et al. 1995, Berkes et al. 2000, Liu et al. 2007). To assess the representative validity of individual archival records, we triangulated content in relation to contemporaneous records (Kyvig and Marty 2000, Hsieh and Shannon 2005). We then constructed a wildfire management narrative for each ownership group by integrating key archival document passages into the historical framework. Where directed by primary source evidence, we adjusted the initial framework (e.g., chronology dates, phase title and characterization).

Ecological data collection and analysis

We used several forest structure metrics to assess current landscape resilience to high-severity wildfire by ownership: resilient forest structure, canopy cover class, and tree size class (Table 2). Resilient forest structure is defined as frequent-fire potential vegetation type units (moist mixed conifer, dry mixed conifer, and ponderosa pine) having large trees and open canopy (tree size ≥ 50 cm and 10–40%

Table 3. Evolution of wildfire management behavior among U.S. Forest Service, private corporate, and tribal landowner groups.

Historical framework stage	Wildfire management behavior category	U.S. Forest Service	Private corporate	Tribal
Stage I: establishment	Wildfire incident management	Suppress all fire incidents	Suppress all fire incidents	Suppress all fire incidents
	Activity fuel management	Pile burn; also swamper burn, lop/scatter	Variable: broadcast burn, lop/scatter, no treatment	Pile burn
	Forest fuel management	No treatment	No treatment	No treatment
Stage II: systemization-centralization	Wildfire incident management	Suppress all fire incidents	Suppress all fire incidents	Suppress all fire incidents
	Activity fuel management	Pile burn	Variable: generally, pile burn; some broadcast burn	Pile burn
	Forest fuel management	No treatment	No treatment	Mixed practices: generally, no treatment; limited experimental prescribed burn
Stage III: reevaluation	Wildfire incident management	Suppress most fire incidents, pilot testing of wildland fire use	Suppress all fire incidents	Suppress all fire incidents
	Activity fuel management	Pile burn; also broadcast burn	Pile burn	Broadcast burn, pile burn, jackpot burn
	Forest fuel management	Prescribed burn	Primarily manage fire risk through forest harvest to low basal area; construct fuel breaks along parcel boundary	Prescribed burn
Stage IV: redirection-reorganization	Wildfire incident management	Mixed practices: suppress most fire incidents, Wildland Fire Use (limited)	n/a	Suppress all fire incidents
	Activity fuel management	Pile burn fuel	n/a	Mixed practices: broadcast burn, pile burn fuel, jackpot burn
	Forest fuel management	Mechanical treatment, prescribed burn	n/a	Mechanical treatment, prescribed burn

canopy cover), or tree size ≥ 38 cm, with moderate canopy cover (40–60% and single canopy layer). Wildfire-resilient structural attributes are based on historic forest conditions and fire regimes (Hagmann et al. 2014, Merschel et al. 2014; for details of forest metrics, see Spies et al. 2017). Current forest structure was characterized using the gradient nearest neighbor method (Ohmann et al. 2011) based on 2008 imagery and inventory plots (Spies et al. 2017). Forest and vegetation structure were classified into seven size classes (0, < 12, 12–25, 25–37, 37–50, 50–75, and > 75 cm), four canopy cover classes (< 10%, 10–40%, 40–60%, and > 60%), and two classes representing either single- or multistoried stands.

RESULTS

Evolution of wildfire management behavior among large landowner groups

U.S. Forest Service

During the agency establishment decades (stage I, 1905–1924), logging slash from extensive harvest operations in ponderosa pine and mixed conifer forests posed a major fire hazard (Munger 1917). Federal foresters responded by treating harvest fuel (nonmerchantable harvest material, or post-harvest debris) and suppressing fire (Table 3). Treatments primarily consisted of piling and burning (“pile-burn”) the slash (Munger 1917, Weaver 1928), although on dry pumice soil sites, lop and scatter was employed experimentally to facilitate reforestation (Munger 1910, 1917). The systemization-centralization stage (stage II, 1924–

1970s) was characterized by stasis, rather than adaptation (Table 4). DNF and FNF foresters continued to deal with wildfire hazard through fire suppression and harvest fuel treatment while not directly treating forest fuels. For example, over the 5-yr period from 1955–1959, DNF managers contained 135 ignitions to an annual average of 39 ha burned (Taylor 1959). Thus, USFS behavioral stasis spanned seven decades (stage I, 1905–1924; stage II, 1924–1970s).

Reevaluation stage (stage III, 1970s–1995) behavioral shifts developed in two categories: (1) fire incident response expanded to include wildland fire use (lightning fires not suppressed in specified zones, e.g., Wilderness Areas [van Wagendonk 2007]); and (2) hazard reduction through treatment of forest fuels. These adaptation trends expanded during the near-current redirection-reorganization stage (stage IV, 1995–2010). Forest fuels were (and are) treated both by prescribed fire and mechanically, with mechanical treatment accounting for most acreage (DNF: 88%; Winema portion of FWNF: 91%; Fremont portion of FWNF: 76%; based on NFPORS data). Multistage treatment (mechanical treatment followed by prescribed burn) was often preferred. Managers treated roughly 1–2%/yr of the available land base (area where treatments were permitted), although the proportion may vary widely (Charnley et al. 2015). WUI treatment is a priority (Charnley et al. 2015). We detected minor behavioral variation between the DNF and FWNF, for instance, regarding the timing of adaptive shifts. The DNF adopted wildland fire use and forest fuel reduction somewhat earlier than the FWNF (1978 vs. 1980s).

Table 4. Summary of wildfire management change or status quo by ownership group across historical framework stages. “Change” indicates a management shift from the status quo (during stage I, “change” indicates the introduction of management practices). “Status quo” indicates that the status quo is maintained relative to the previous period.

Framework stage	U.S. Forest Service			Private corporate			Tribal		
	Wildfire incident response	Activity fuel treatment	Forest fuel treatment	Wildfire incident response	Activity fuel treatment	Forest fuel treatment	Wildfire incident response	Activity fuel treatment	Forest fuel treatment
Stage I: establishment	Change	Change	n/a	Change	Change	n/a	Change	Change	n/a
Stage II: systemization-centralization	Status quo	Status quo	Status quo	Status quo	Change	Status quo	Status quo	Status quo	Change
Stage III: reevaluation	Change	Status quo	Change	Status quo	Status quo	Status quo	Status quo	Status quo	Change
Stage IV: redirection-reorganization	Status quo	Status quo	Change	n/a	n/a	n/a	Status quo	Status quo	Change

This variability was because of the selection of the DNF as a test unit for the Pacific Northwest Region “as an interim step in implementation of the revised Fire Management Policy,” promoting early experimentation with adaptive approaches (DNF 1978).

Private corporate owners

The private corporate ownership group is somewhat heterogeneous, characterized by diverse current land management practices and histories (Charnley et al. 2017). We report management trends that apply broadly while acknowledging management diversity associated with factors such as organizational type (e.g., family ownership, Real Estate Investment Trust) and operation size. Prior to old-growth harvest, private owners in the Oregon dry pine region held more pine volume (48.6%) than the USFS (38.5%) or Indian reservations (12.8%; Munger 1917).

Initially (establishment stage, 1911–1924), private owners safeguarded their property from wildfire risk by treating harvest fuel and suppressing fire. Managers generally continued these two practices during the systemization-centralization stage (1924–1997). The main behavioral development pertained to harvest fuel treatment: some owners shifted from less labor-intensive, broadcast burns to pile burns (Table 3). Development of the forest science concept of “reserve stand” (immature trees reserved for future harvest) promoted this behavioral shift (Munger 1917, Weaver 1928, Western Pine Association 1940).

During the reevaluation stage (1997–2010), many private corporate managers adapted to wildfire hazard increase by constructing fuel breaks along parcel boundaries and roadsides to manage fire risk posed by neighboring owners. In addition, fuel was managed through timber harvest to maintain a low basal area, between-tree spacing, and thinning of submerchantable wood when financially feasible. Forest surface fuel was generally not treated, other than in specific circumstances (e.g., participation in community wildfire protection plans, a mechanism to assess wildfire risk and prioritize treatments). Piled slash was burn-treated. Wildfire incidents have been managed through suppression throughout the study period (Table 4).

We did not find evidence that the private corporate ownership group had adopted adaptive practices characteristic of the redirection-reorganization stage, although there is evidence of reevaluation-stage rethinking. In general, private owners have responded to increased wildfire hazard in frequent-fire forests with comparatively limited adaptation (e.g., fuel break construction coupled with commercial thinning and forest harvest as fuel management tools), yet have not shifted away from the past practices of stages I–II that historically contributed to fuel accumulation. However, management adaptation varies among individual owners in association with ownership group diversity.

Tribal owners

Until the early 20th century, east Cascades tribes applied controlled fire to promote culturally important products, particularly huckleberry shrubs (*Vaccinium* spp.; French 1999). Conversely, early reservation foresters perceived all fire as a serious risk to valuable commercial timber (Heritage 1925), and thus, this practice was perceived as incongruous with commercial forest management. However, informants noted that tribal members continued to apply fire to promote cultural resources “during my grandmother’s time,” after the start of professional (agency) forest management.

Management of tribal forestlands by U.S. government forest managers formally began after 1910, when the Forestry Branch of the BIA was established (Newell et al. 1986), although mills were built to process lumber for local use (administrative buildings, tribal houses) on the WSR before 1910 (Logan 1982). Initially (establishment stage, 1910–1924), foresters controlled wildfire hazard by suppressing fire and treating harvest fuel (Table 3). A large volume of pine and other mixed conifers grew on the WSR (Hagmann et al. 2014). Managers recognized “the importance [of] protection of over \$10 million of timber” (Heritage 1925) from wildfire, resulting in construction of a wildfire suppression system (fire incident detection, communication, transportation; Logan 1982). Activity fuel hazard was controlled using pile-burn treatments, modeled on standards of the USFS and codified by BIA Timber Sale Regulations (Sells 1920).

During the systemization-centralization stage (1924–1975), the major adaptation to wildfire hazard change was experimental treatment of forest fuels (Table 4). Managers reported, “Fuel has built up in the Warm Springs forest until it is very hazardous” (Weaver 1957a); and, “of the many problems...none are more difficult than those arising from the forest fire exclusion [of]...the past 40 years” (VanSickle 1957). Hazard consisted of dense understory seedling and sapling accumulation (“reproduction jungles,” “many thousands of seedlings per acre”) interspersed with shrub thickets (e.g., bitterbrush), “heavy needle mats of many years’ accumulation,” and “countless thousands of snags and windfalls” (Weaver 1957b). Treatments were applied experimentally to generate silvicultural knowledge, reduce fire hazard, and promote ponderosa pine reforestation (Nash 1957, Weaver 1957c). By 1956, foresters control-burned pine and mixed conifer stands, as well as incense cedar (Logan 1982:77), with the intent to “ultimately cover [treat] all the ponderosa pine stands” (VanSickle 1957, Hoffman 1959).

The main management evolution of the reevaluation (1975–1995) and redirection-reorganization (1995–2010) stages was expanded forest fuel treatment. By 1981, tribal foresters applied prescribed fire as an officially approved tool (Logan 1982), unlike past experimental use. During the 2002–2012 period, 2350 ha were treated annually, on average, according to NFPORS records. Mechanical treatments were primarily employed (61% of treated area), yet prescribed fire was substantial (39%). Treatments were designed to increase forest resilience to wildfire and reduce crown fire hazard by reducing vertical (ladder) and horizontal fuel connectivity and expanding between-tree distance. Other developments were broad-scale forest restoration projects and multiphase projects (thinning, mowing or mastication, and controlled burn, in sequence), designed to reduce the risk of escaped prescribed burns.

Evolution of wildfire management formal institutions among large landowner groups

A number of federal and state laws and policies were developed over the 20th century to direct wildfire management behavior by Oregon’s large landowners. Many of these formal institutions pertained to multiple ownerships, although some were ownership specific. We describe them here by historical stage because of the interrelated, cross-ownership nature of law and policy in the study area, and by category of wildfire management (fire incidents, activity fuels, forest fuels).

Establishment and systemization-centralization stages (stages I and II)

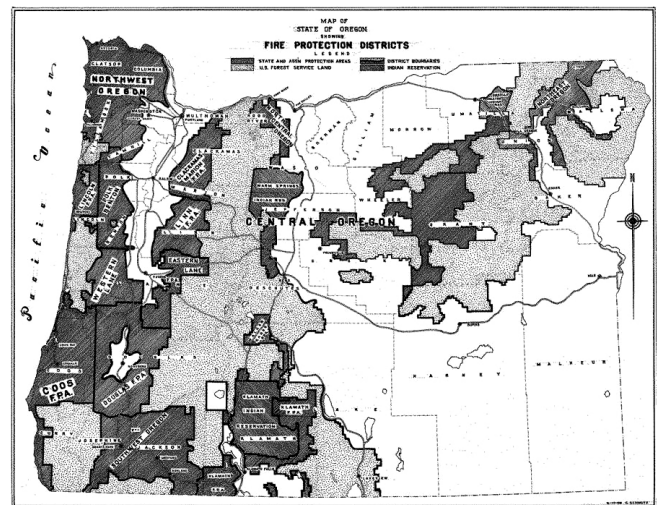
Wildfire law and policy during the establishment stage were consistent across large ownerships in all three wildfire management categories (Table 5). Federal and state laws directed managers both to suppress wildfire and treat harvest fuel, and no ownerships were directed to treat forest fuels. Policy consistency across ownerships was due to the mutually held priority to protect timber from wildfire loss.

In addition to cross-ownership consistency, cross-ownership cooperation was a major theme of USFS-private corporate owner wildfire law. Cooperation was a directive between USFS and tribal ownerships as well, although generally codified via agreement documents rather than law. Federal and state laws were structured to dovetail with one another. The 1911 *Weeks Act* (36 Stat. 961) directed the USFS to cooperate with states to protect forested

watersheds from wildfire. For instance, federal matching funds were available for fire patrol salaries (<http://www.foresthistory.org/ASPNET/Policy/WeeksAct/Implementation.aspx>). USFS goals to control hazards posed by logging slash from adjoining private lands drove the cooperation directive. Thus, the Act pertained only to private lands and national forests within the same forested watershed. However, it stipulated that wildfire control funds be dispersed only to states that had a state fire control agency (USDA-FS 1961) and forbade exceeding the state’s funding level. The same year, the 1911 Oregon Forest Fire Laws created the Oregon Department of Forestry (ODF) and appointed a State Forester (State of Oregon 1919, ODF-INR 2005, Hunt-Jones 2008). These laws authorized fire wardens to patrol private forestry operations and enforce compliance with slash disposal standards.

For private corporate owners, the Oregon Forest Fire Laws together with the 1911 Articles of Incorporation of the Oregon Forest Fire Association created an organizational structure to suppress wildfire incidents. The federal *Weeks Act* promoted state creation of Forest Protection Districts, a primary administrative unit of the Oregon forest protection system (Fig. 3), by tying receipt of federal wildfire cost-sharing funds to requirement of a state forest protection system. These districts functioned as the state-level structure that interfaced with the locally organized fire patrols that were beginning to coalesce in the eastern Cascades (e.g., Klamath Forest Protection Association [FPA] in 1908, Walker Range FPA in 1927, Black Butte FPA in 1937) and statewide. The purpose of these FPAs was to protect landowners’ timber property in the associated district from wildfire loss.

Fig. 3. Example representation of private corporate institutions, particularly during the systemization-centralization stage: Fire Protection Districts (also known as Forest Protection Districts), 1958. Oregon Department of Forestry and private industrial owners historically shared joint responsibility to manage wildfire hazard through district structure. Source: Oregon State Archives.



We also found differences in formal institutions among ownerships, despite general uniformity. For private corporate owners, laws prioritized protection of private property, unlike those of USFS and tribal lands. The Oregon Forest Fire Laws,

Table 5. Evolution of wildfire formal institutions among U.S. Forest Service, private corporate, and tribal landowner groups.

Stage of CHANS [†] -historical framework	Formal institution category	U.S. Forest Service (USFS)	Private corporate	Tribal
Stage I: establishment	1. Wildfire incident management rules, including those for cross-ownership cooperation	• 1911 <i>Weeks Act</i>: called for federal, state, and private cooperation to manage fire incidents; authorized federal funding for USFS to cost-share forest protection with states	• 1911 Oregon Forest Fire Law: created Oregon Department of Forestry; authorized appointment of state forester and fire wardens; obligated all able-bodied individuals to assist fire-fighting if enlisted by a warden or face a fine • 1913 <i>Oregon Fire Patrol Act</i>: required Oregon forest owners to provide fire protection of their land or pay tax	• Tribal Trust Doctrine (1831): principle of U.S. obligation to manage tribal resources in ways that uphold treaty rights and steward tribal sovereignty; justification for suppress-all-fires practice • 1910 <i>Indian Omnibus Act</i>: created Bureau of Indian Affairs Forestry Branch, leading to wildfire suppression policy • Cooperative agreements (1910s–1940s) regarding fire surveillance and suppression forged between U.S. Department of Agriculture and U.S. Department of the Interior
	2. Harvest fuel treatment rules	• USFS logging debris disposal guidelines: directed treatment of harvest slash corresponding with policy to administer “public lands...to perpetuate the forest... [including] absolute fire protection” (Munger 1917)	• 1911 Oregon Forest Fire Law: required forest owners to burn harvest fuels every year, otherwise face a fine • 1913 <i>Oregon Fire Patrol Act</i>: authorized wardens to fine private owners who fail to treat hazardous harvest fuels	• 1910 <i>Indian Omnibus Act</i>: created Bureau of Indian Affairs Forestry Branch, which conferred authority to manage tribal timber; practices modeled on USFS, which called for treatment of harvest fuel, primarily via pile-burn
	3. Forest fuel management rules	n/a	n/a	n/a
Stage II: systemization-centralization	1. Wildfire incident management rules, including those for cross-ownership cooperation	• 1924 <i>Clarke-McNary Act</i> (section 2): authorized financial and technical assistance between USFS and states to protect forests via fire control; expanded 1911 <i>Weeks Act</i> • 1935 10:00 A.M. Fire Control Policy: directed managers to “control every fire within the first work period” and if not, by 10:00 A.M. the following morning	• Continuation of stage I rules • 1925 Oregon Forest Fire Laws (updated 1937, 1947, 1954): directed protection of forest private property through fire suppression; state-private cooperation instituted via Forest Protection Associations (FPAs) and associated FPA districts • FPAs authorized to carry out function of state fire wardens • No change	• Continuation of stage I rules
	2. Harvest fuel treatment rules	• No change	• No change	• No change
	3. Forest fuel management rules	n/a	n/a	n/a
Stage III: reevaluation	1. Wildfire incident management rules, including those for cross-ownership cooperation	• 1977 revision of National Forest Fire Policy: amended 10:00 A.M. Fire Control Policy • 1978 <i>Cooperative Forestry Assistance Act</i>: repealed section 2 of <i>Clarke-McNary Act</i>, reducing cooperative fire funding • 1989 National Forest Manual, Interim Directive 23, Prescribed Fire (chapter 5140): called for “new direction on planning and executing... prescribed fires and prescribed natural fires” as an approach to manage forest fuel	• 1997 <i>Oregon Forestland-Urban Interface Fire Protective Act</i>: “Enlists ... property owners to turn fire-vulnerable urban and suburban properties into less-volatile zones where firefighters may ... defend homes from wildfires” • 2009 Oregon Fire Protection of Forests and Vegetation (ORS 477): acknowledged “need for complete and coordinated forest protection system;” affirmed “the preservation ... of forest resources through prevention and suppression of forest fires [is] ... the public policy of the State of Oregon” • Continuation of stage I rules • 1997 <i>Oregon Forestland-Urban Interface Fire Protective Act</i> (Oregon Senate Bill 360): directed operators in wildland-urban interface zones to treat harvest fuel • 2005 Oregon Department of Forestry (ODF) Protection from Fire Program Review Implementation Plan: presented statewide fuels management strategy; recommended treatment of forest fuel via enrollment in federally funded Community Wildfire Protection Plan • 2014 Regional Solutions Participation Plan for ODF: forest fuel treatment included in Fire Program	• Continuation of stage I rules • 1990 <i>National Indian Forest Resource Management Act</i> (NIFRMA): acknowledged U.S. trust responsibility toward tribal forest lands; acknowledged that federal investment in federal lands was “significantly below” investment in USFS, Bureau of Land Management, and private land; directed “protection against losses from wildfire”
	2. Harvest fuel treatment rules	• No change	• Continuation of stage I rules • 1997 <i>Oregon Forestland-Urban Interface Fire Protective Act</i> (Oregon Senate Bill 360): directed operators in wildland-urban interface zones to treat harvest fuel	• No change
	3. Forest fuel management rules	• 1989 Forest Service Manual, Interim Directive 23, Prescribed Fire (chapter 5140): called for “new direction on planning and executing ... prescribed fires and prescribed natural fires” as an approach to manage forest fuel	• 2005 Oregon Department of Forestry (ODF) Protection from Fire Program Review Implementation Plan: presented statewide fuels management strategy; recommended treatment of forest fuel via enrollment in federally funded Community Wildfire Protection Plan • 2014 Regional Solutions Participation Plan for ODF: forest fuel treatment included in Fire Program	• 1990 <i>National Indian Forest Resource Management Act</i> (NIFRMA): included “hazard reduction” and “prescribed burning” as elements of “forest land management” definition

(con'd)

Stage IV: redirection- reorganization	1. Wildfire incident management rules, including those for cross-ownership cooperation	• 1995 Federal Wildland Fire Management Policy: “Wildland fire will be used to protect, maintain, and enhance resources and, as nearly as possible, be allowed to function in its natural ecological role”	n/a	• 1992–2001 Integrated Resources Management Plan of Confederated Tribes of Warm Springs Reservation (CTWSR), and subsequent plans: directed wildfire suppression
	2. Harvest fuel treatment rules	• Continuation of stage I rules	n/a	• 1995 Federal Wildland Fire Management Policy: see USFS entry
	3. Forest fuel management rules	• 2000 National Fire Plan: called for expanded treatment of hazard fuels, fire-adapted ecosystem restoration, and community assistance programs; advocated renewed federal-state-local coordination • 2003 <i>Healthy Forest Restoration Act</i> : directed federal agencies to treat hazardous forest fuel; streamlined environmental assessment process for fuels projects • 2009 <i>Omnibus Public Lands Act</i> , Collaborative Forest Landscape Restoration Program: directive to restore fire-prone forests at broad spatial scale and across ownerships	n/a	• 1992–2001 Integrated Resources Management Plan of CTWSR, and subsequent plans: directive to treat activity fuels, with expanded specification to Forest Management Zone and associated harvest practice • 1992–2001 Integrated Resources Management Plan of CTWSR, and subsequent plans: “management now recognizes the need to systematically plan and reduce this fuel accumulation, while reintroducing fire...” • 2000 National Fire Plan: see USFS entry • 2003 <i>Healthy Forest Restoration Act</i> : see USFS entry • 2004 <i>Tribal Forest Protection Act</i> : promoted tribal government-federal agency cooperation to reduce risk to tribal forest resources posed by fuel of adjoining federal land • 2009 <i>Omnibus Public Lands Act</i> , Collaborative Forest Landscape Restoration Program: see USFS entry

³Coupled human and natural system.

together with the 1913 *Forest Patrol Act*, stipulated landowner duty to prevent fire ignition or spread to neighboring property, as well as penalties for failure to comply. Under these laws, private corporate owners bore responsibility to fulfill two interlinked wildfire management practices: (1) provide “adequate protection” against fire start or spread, either by providing a fire patrol or paying a forest tax; (2) abate hazard on cut-over land, specifically to “burn annual slashing” or face a fine, thereby controlling risk to neighboring private property (ODF-INR 2005).

For managers of tribal forests, a distinguishing formal institution was (and is) fiduciary responsibility to manage Indian reservation forests for the benefit of Indian tribes. Tribal trust doctrine (1831) obligated managers to steward tribes’ sovereignty by protecting tribal resources (Fuller 1989, Clow and Sutton 2001, McQuillan 2001). Thus, managers were responsible to implement practices designed to avert loss by wildfire or other disturbances. The 1910 *Indian Omnibus Act* provided the mechanism to fulfill trust doctrine by creating the Forestry Branch of the BIA. Although this act applied to tribal ownerships only, the BIA Forestry Branch was essentially modeled after the USFS, and the legislation called for protecting tribal timber from wildfire risk using the same methods that the USFS used: piling and burning harvest activity fuels and fire suppression.

During the systemization-centralization stage, the legal and policy directives of the establishment stage became more coordinated among USFS and private corporate owners (Bramwell 2013). The federal 1924 *Clarke-McNary Act* (16 USC § 565) expanded on the *Weeks Act* to strengthen mechanisms for controlling fire spread from private to federal land. The law did so by increasing federal cost-sharing funds to FPAs, the local-level governance and management unit, channeling them through the USFS to the state (ODF) and then to individual FPAs (Diehl 1953). Consequently, *Clarke-McNary* expanded the nascent

cooperative network that linked management on national forest, state (ODF), and private industrial ownerships. A series of corresponding Oregon Forest Laws (1925, 1937, 1947, 1954) expanded private owners’ responsibility to control wildfire hazard, and if shirked, liability. Inspection handbooks standardized harvest fuel management practices and enforcement (e.g., OSBF 1946, OSBF 1954).

Additionally, Congress passed laws directing sustained-yield forest management on both USFS (1944 *Sustained-Yield Management Act*) and tribal ownerships (1934 *Wheeler-Howard [Indian Reorganization] Act*). Both of these laws directed managers to block wildfire and other disturbances that risked interfering with a steady flow of timber volume.

The 10:00 A.M. Control Policy (DNF 1978, Pyne 2009) was a key policy development for DNF and FNF managers during the systemization-centralization stage. Adopted in 1935 under USFS Chief Silcox, this policy tasked managers with fire suppression that was “fast, energetic, thorough, and [regardful of] personal safety.” Its goal was to control “every fire within the first work period;” if not achieved, then by 10:00 A.M. the following morning (DNF 1978). Though this policy applied only to national forests, it set a management standard for tribal and private corporate managers given the acknowledged leadership of the USFS during this period.

Reevaluation and redirection-reorganization stages (stages III and IV)

The transition to the reevaluation stage on USFS lands was indicated by the 1977 modification of the “very rigid” 10:00 A. M. policy and 1978 repeal of *Clarke-McNary Act* sections authorizing cooperative wildfire suppression (DNF 1978:1, van Wagtenonk 2007). Policy revisions called for “a balanced fire management program which is cost effective and commensurate

with threats...” (DNF 1978). In 1978, DNF foresters identified zones suitable for a let-burn policy as an alternative to the uniformly applied, unvarying 10:00 A.M. policy. These adaptations were designed to “provide for an orderly transition from the old policy to the new,” which would enable “full integration of fire use in ...land management” by 1983 (DNF 1978:1–2). In 1989, the Forest Service Manual provided “new direction on planning and executing management ignited prescribed fires...” (USDA-FS 1989). However, the potentially competing policy of fulfilling timber production targets persisted.

On tribal forests, key policy developments demarcating a reevaluation stage transition include the 1975 *Indian Self-Determination and Education Assistance Act* (25 USC § 5321) and 1990 *National Indian Forest Resources Management Act* (25 USC § 33). The Self-Determination law empowered tribes to run their natural resource management departments and directly employ staff. On WSR, resultant management plans “now recognize the need to systematically plan and reduce ... fuel accumulation, while reintroducing fire...” (CTWSRO 1993).

Most recently (redirection-reorganization stage), federal laws and policies have directed USFS and tribal forest managers to restore fire-prone forests, of which forest fuel treatment is one component (e.g., the 2000 National Fire Plan [USDA-USDI 2000]; the 2003 *Healthy Forest Restoration Act* [16 USC § 6501–6517]). These formal institutions span the U.S. Department of Agriculture and the U.S. Department of the Interior, promoting cohesion among directives to USFS and tribal land managers. Federal laws passed since the National Fire Plan have augmented the directive for DNF, FWNF, and WSR managers to treat forest fuels (e.g., the 2009 *Federal Land Assistance and Management Enhancement Act* [43 USC § 1701, 1748b], the *Collaborative Forest Landscape Restoration Act* [16 USC § 7301–7304]; USDA-FS and USDI-OWFC [2011]). Despite these legislative developments, tribal forest managers highlighted constraints posed by reductions in fuels treatment funding. Described by tribal informants as “our limiting factor,” one manager observed, “Right now we’re [fire management] struggling ... with reductions of budget ... How are we supposed to meet that goal [of social-ecological resilience] in National Cohesive Strategy? That’s a struggle for us.”

Regarding private corporate owners, we identified two formal institutional developments that signaled transition into a reevaluation stage. This development pertained to nascent rethinking about forest fuel treatment. Through the 1997 *Oregon Forestland-Urban Interface Fire Protection Act*, ODF enlisted owners to reduce fire hazard via vegetation treatment. However, this law is directed at urban and suburban landowners, whose restoration affects only a small proportion of the land area. Second, the 2005 ODF Protection from Fire Implementation Plan presented 12 recommendations to develop a statewide fuels management strategy that spans private, state, and federal partners (ODF-INR 2005). For instance, the Plan encouraged private corporate landowners to participate in Community Wildfire Protection Plans authorized and federally funded by the *Healthy Forest Restoration Act* (16 USC § 6511); for corporate owners, this is the principal instrument to access public funds to treat fuels.

Evolution of wildfire management informal institutions among large landowner groups

We organized informal institutions that influence wildfire management into four categories: cultural norms, the knowledge system and fire paradigm on which land management is based, forestry goals regarding production (e.g., sustained yield), and forest management economic goals (e.g., community economic stabilization). Interview and archival data indicate that informal institutions initially differed somewhat (stage I), then coalesced, anchoring a lengthy period of convergence toward cross-ownership coordination (stage II). They later diverged again among ownership groups (stages III, IV; Table 6). As with wildfire formal institutions, informal institutions sometimes crossed land ownership boundaries.

Establishment and systemization-centralization stages (stages I and II)

During the establishment stage, USFS, private corporate, and tribal ownerships mutually held a conventional science knowledge system and fire paradigm. In this scientific worldview, fire and other environmental disturbances should be minimized to promote forest production. USFS and tribal managers, and eventually, some private corporate owners also adopted the related forestry and economic ideals of continuous, sustained-yield forest crop production and long-term revenue generation to stabilize rural community economies. In contrast, many private corporate owners harvested at unsustainably high rates (90–95% of basal area) in the 1930s, according to USFS forest economist calculations (Hodgson 1938). In response, DNF and FNF managers instituted a disturbance-averse, integrated federal-private rotation system. After private logging companies harvested USFS and private stands, cutover private parcels would be transferred to federal ownership for reforestation and future harvest. These production and economic ideals depended on aggressive fire suppression. Similarly, under BIA Commissioner John Collier (1933–1945), tribal forests were to be managed in a “perpetually productive state by providing effective protection” (Newell et al. 1986).

Over time, the forest production ideal of many early to mid-20th century private corporate owners evolved from maximized yield (“cut and run”) to sustained yield harvesting through ties to organizations that drew them together with USFS scientists. Many were members of the Western Forestry and Conservation Association (established in 1924) and the Western Pine Association (established in 1931) or were involved with the Oregon-Washington Forest Research Council (established in 1955), an outgrowth of the Western Forestry and Conservation Association. Key ideals were conservation and continuous production of forest crops (e.g., via tree farms) and control of fire hazard. These ideals, embedded in forestry organizations, reinforced state laws to treat harvest fuels (Western Pine Association 1949).

Moderately dissimilar cultural norms were embedded in the three ownership groups despite sharing forest production and economic ideals. Among private corporate owners, decentralized, situational norms were embedded in each semiautonomous FPA (Fig. 3). In contrast, DNF and FNF managers operated within a professional, scientifically trained, expert forestry cadre. Within

Table 6. Evolution of wildfire informal institutions among U.S. Forest Service, private corporate, and tribal ownership groups.

Stage of CHANS ¹ -historical framework	Informal institutional category	U.S. Forest Service (USFS)	Private corporate	Tribal
Stage I: establishment	1. Cultural norms of organization	- Centralized, hierarchical, decision-making norms - Planning-centric, data-driven, decision-making norms - Professional, scientifically trained, expert forestry cadre	- Semiautonomous, locally accountable, decision-making norms - Prioritization of private property protection in fire management decisions	Disparate norms: hierarchical, planning-centric, decision-making norms; pragmatic, situationally appropriate norms; emulate USFS professional forestry cadre despite scarce funding and resources
	2. Knowledge system and fire paradigm	Conventional science fire management paradigm: manage fire hazard via fire suppression and activity fuel treatment	Hybrid of conventional science fire management paradigm and pragmatism: manage fire hazard mainly via suppression	Conventional science fire management paradigm, following USFS
	3. Forestry ideal	- Efficiency-oriented conservation - Maintain stable production of timber volume; employ reserve stand concept	Maximize forest production	- Efficiency-oriented conservation - Extensive forest management: selective harvest of big trees, spanning large area
	4. Forest economic ideal	Forest resource purpose: build local, regional, and national economy	Maximize revenue	Forest resource purpose: build reservation economy; also build forest management system, e.g., road network
Stage II: systemization-centralization	1. Cultural norms of organization	- Stasis: stage I norms continue - Risk-averse norms predominate	Stasis: stage I norms continue	- Stasis: stage I norms predominate, emulating USFS professional forestry cadre - Pragmatism - Among some managers, cultural norms shift (e.g., tolerate experimental prescribed burn)
	2. Knowledge system and fire paradigm	Stasis: conventional science fire management paradigm of stage I continues	Adopt conventional science fire management paradigm of USFS: manage fire hazard via both suppression and activity fuel treatment	Stasis: conventional science fire management paradigm of stage I predominates
	3. Forestry ideal	Sustained yield via forest rotation	Diverse ideals within ownership group: maximize short-term harvest; continuous forest production (tree farm concept)	- Some managers begin questioning conventional management paradigm - Sustained yield - Some shift of ideals: extensive forest management, per stage I; intensive forest management to maximize production via even-aged management
	4. Forest economic ideal	Community economic stabilization	Diverse ideals within ownership group: maximize short-term revenue; maximize long-term revenue and community stabilization	Community economic stabilization
Stage III: reevaluation	1. Cultural norms of organization	Conflict of new vs. old norms within organization: question conventional fire management paradigm; adaptive management; planning-centric culture; risk-averse culture	- Partial stasis: norms of stage I generally continue - Norms of cross-ownership collaboration burgeon	Conflict of new vs. old norms within organization: question conventional fire management paradigm; cultural resources become a management focus; planning-centric culture with adherence to planning process, including Tribal Council review; risk-averse culture
	2. Knowledge system and fire paradigm	Fire management paradigm in transition: conventional science; ecosystem science, with ecological uncertainty regarding fire acknowledged; adaptive management	- Fire management paradigm of stage II generally predominates - Ecological resilience concept considered by some owners	Fire management paradigm in transition: conventional science; ecosystem science and fire science (target for future fires to mimic natural fire frequency)
	3. Forestry ideal	Divergent ideals: sustained yield; multiple use	Diverse ideals within owner group: sustained yield; accelerated harvest; long-term forest ecosystem health	Transition between ideals: intensive management and production; "balanced management," with dual goals of resource production and ecosystem maintenance
	4. Forest economic ideal	Community economic engagement	Diverse ideals, as in stage II	Stasis: ideal of stage II continues
Stage IV: redirection-reorganization	1. Cultural norms of organization	Diverse norms: norm of wildfire decisions based on restoration goals and situational conditions; norms of cross-ownership collaboration	n/a	Diverse norms: conventional timber-oriented management with timber valued as important contributor to tribal economy; cultural resources and traditional forest uses valued; norm of wildfire decisions based on restoration goals
	2. Knowledge system and fire paradigm	Fire management paradigm of stage III moderately shifts: forest landscape restoration ecology and ecological resilience perspectives introduced; ecosystem science knowledge system; conventional science knowledge system persists	n/a	Fire management paradigm of stage III moderately shifts: ecosystem science knowledge system, including restoration ecology; traditional ecological knowledge recognized as relevant to wildfire decisions; conventional science knowledge system persists

(con'd)

3. Forestry ideal	• Diverse ideals: ecosystem management; ecosystem services-based forestry to manage forests to maintain ecosystem services; forest production considered one of many services; continue forest harvest (meet timber targets), although at reduced rate	n/a	• Balanced management predominates, as in stage III • Shift toward ecosystem management framework
4. Forest economic ideal	• Community economic benefit through diverse forest ecosystem services	n/a	• Diverse ideals: forest harvest to promote community economic stabilization continues; timber revenue considered one of many objectives, not the sole objective

[†] Coupled human and natural system.

this centralized, hierarchical organization, acceptable wildfire management decisions were shaped by a narrow agency mission in combination with prescriptively interpreted forest science data. These norms are vividly manifest in USFS fuel type maps produced by the 1930s–1940s fire control planning program (Fig. 4). The USFS research program on fire control and sustained yield forest management (e.g., Munger 1910, 1917, 1951, Munger and Westveld 1931) guided fire control planning. Scientific studies examined physical fuel properties, which generated knowledge regarding two variables: rate of fire spread and resistance to control. DNF and FNF managers then applied this knowledge to develop improved fire control plans based on the spatial distribution of these variables. Finally, tribal forest managers were characterized by norms moderately distinct from the USFS. These managers emulated the planning-driven cultural norms of the USFS professional forestry cadre. However, at the individual reservation scale, acceptance of pragmatic adaptations (e.g., experimental prescribed burn treatment of forest fuels [Fig. 5]) simultaneously influenced managers. Tension between agency norms of hierarchical adherence vs. pragmatism sometimes put WSR managers in a bind (Weaver 1957a,b).

Overall, during the systemization-centralization stage, we found that cross-ownership coordination increased. Among all three ownership groups, three of the four informal institutional categories (knowledge system and fire paradigm [conventional science], forest production ideal [sustained yield], forest economic ideal [community economic stabilization]) gradually converged over several decades (1905–1930s [including establishment stage years]), resulting in broad-scale institutional coordination during the 1940s–1970s.

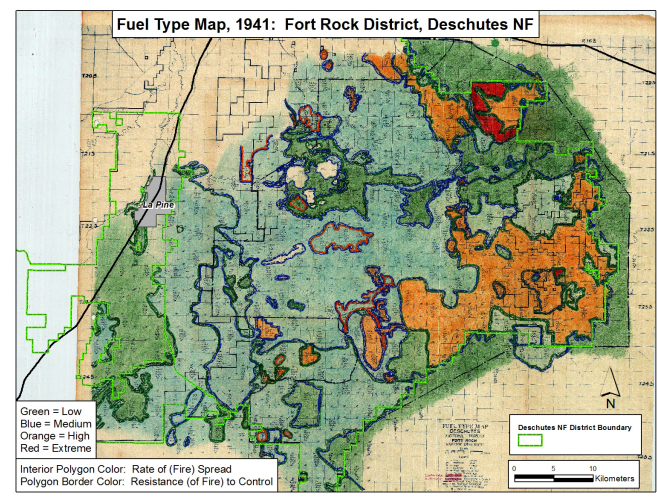
Reevaluation and redirection-reorganization stages (stages III and IV)

During the reevaluation and redirection-reorganization stages, informal institutional change was greater for USFS and tribal ownerships than for the private corporate group, although more so for some corporate owners than others. This divergence applied to all four informal institutional categories.

Forest production ideals shifted among USFS managers to an ecosystem management or ecosystem services approach and among tribal managers to “balanced management” (CTWSRO 1993); these shifts were both departures from the historical ideal of continuous forest production. Forest economic ideals shifted in tandem. For example, a DNF interviewee expressed the economic ideal of generating community benefits through diverse forest services: “People from all over the world come here to mountain bike. It brings an economy with it. This community

relies on this forest that surrounds them for their livelihood.” Nonetheless, maintaining timber production targets remains an important forest management consideration (Smith et al. 2011). Among WSR managers, timber production remains the primary forest economic objective, although it has diminished compared to stage II and is currently only one of many ecosystem benefits. In 2002, timber sale receipts were projected to generate 15–20% of WSR tribal income in addition to approximately 84 mill jobs and 33 logging company jobs (CTWSRO 2003). For private corporate owners, forest production and economic ideals changed little compared to stage II. Nevertheless, within-group heterogeneity resulted in diverse economic models for revenue generation and production to meet economic goals (Charnley et al. 2017).

Fig. 4. Example representation of U.S. Forest Service institutions during the systemization-centralization stage. There was a cultural norm of centralized, planning-focused management by a professional forester cadre, which reinforced the 10:00 A.M. Fire Control Policy. Fuel Type Map, a component of U.S. Forest Service hazardous fuel management and fire control planning program, circa 1925–1940. Source: Fire Atlases, National Archives and Records Administration, Pacific Alaska Region Facility, Seattle, Washington, USA.



Within the USFS during stage III (reevaluation), cultural norms and knowledge systems generally shifted in tandem with forest production and economic ideals, yet these informal institutions were characterized by conflict between old and new ideals. As an

adaptive management paradigm developed, questioning of the conventional fire science paradigm became acceptable (DNF 1978), but a risk-averse culture persisted. In addition, pushback by senior officials to wildfire cost overruns called into question the entrenched practice of hard-and-fast response to all wildfire incidents, regardless of size (DNF 1978). During stage IV, norms shifted toward a collaborative, agency–community bridge-building approach to wildfire management, as embedded in Forest Landscape Restoration Collaboratives, Fire Learning Networks, and Community Wildfire Protection Plans. A DNF manager underscored this shift: “The only way we’re going [to] get any [forest fuel treatment] planning through is to get those groups supporting what we’re doing on a landscape level... Those collaboratives are hugely important to us [now] and in the future.”

Fig. 5. Example representations of tribal institutions, particularly during the systemization-centralization stage. (A) Tribal community forestry-based economic development, 1959. Source: Weaver (1959). (B) Cross-ownership cooperation between tribal ownership and the U.S. Forest Service to control wildfire hazard. Source: Jones and Galloway (1919). (C) Tolerance for limited experimentation to manage wildfire hazard and promote reforestation of commercial forest species: experimental application of prescribed burn. Source: Weaver (1960).



On the WSR, key informal institutional developments of the reevaluation stage include an ecosystem management knowledge system and the norm of expanded Tribal Council and tribal community participation. These developments grew from the 1975 *Indian Self-Determination and Education Assistance Act*, which gave tribes authority to direct resource management, and the early 1990s establishment of the WSR Branch of Natural Resources. The BIA maintained its fiduciary role, however. The shift in knowledge system toward ecosystem management led managers to consider practices to restore historical fire regimes. Simultaneously, values to maintain cultural resources, not timber revenue alone, weighed into wildfire decision making. These expanded norms sometimes imposed new constraints on fire management options. Regarding cultural values, a fire manager elaborated: “Wildlife, we didn’t want to [controlled] burn up all the sage...[and] bitterbrush in there because ... deer...horses, and cows eat that [vegetation]. With Cultural Resources, we talked

about all ... the root digging [meadows]..., there are certain times of year we can’t burn...” In addition, consideration of timber harvest effects became a norm in fire managers’ decisions, increasing complexity. For instance, the spatial pattern of timber harvest units poses difficult decisions. These units are dispersed and sometimes adjacent to unharvested, fuel-dense stands. One tribal manager observed, “...the fuel loading between these [harvest] blocks [is] so thick that if fire generates in there, what are we going to do?” In sum, the fire paradigm of WSR managers shifted somewhat, and the array of community-prioritized forest values expanded, putting managers in a difficult decision-making situation.

For the private corporate group, a characteristic norm has been private property protection, and the knowledge system has been a conventional science fire management paradigm (fire suppression-focused wildfire management). Over the 1905–2010 study period, informal institutions embedded in the ownership group and those of affiliate management organizations (FPAs, ODF) have been comparatively static (ODF-INR 2005, Hunt-Jones 2008). Norms of property protection were consistent with owners’ financial goals and economic constraints: forest management by private owners is profit driven, and owners may not have the resources to invest in noncommercial forest treatments.

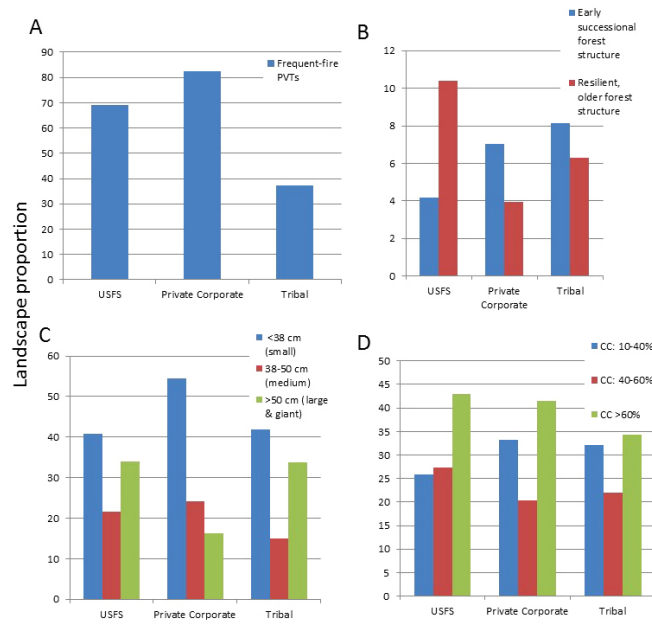
Current forest structure variation among large landowner groups

We examined variation in current wildfire-resilient forest structure by ownership group to assess the influence of wildfire management history as shaped by institutional history. Forest composition, measured by potential vegetation type, varies by ownership (Fig. 6A). The area of frequent-fire forest potential vegetation types as a proportion of total land area is highest among private corporate owners (82.3%), intermediate for USFS lands (69.0%), and lowest on tribal lands (37.4%). Thus, private corporate forests are more vulnerable to wildfire than are other large ownerships because of the comparatively high proportion of frequent-fire forest. We controlled for inherent variation in tree size class and forest canopy cover among ownership groups because of the difference in forest composition by limiting our analysis to frequent-fire forest potential vegetation types.

The area of older, wildfire-resilient forest structure is largest for national forests, intermediate for tribal forests, and smallest for private corporate forests (10.4%, 6.3%, and 3.9%, respectively; Fig. 6B). Wildfire-resilient structure means that the stand is unlikely to carry a crown fire; resilience indicators include large trees and an open canopy, resulting in widely spaced trees and an absence of ladder fuels. The area of early seral stage forest (highly vulnerable to high-severity fire) is relatively large on private corporate and tribal forests (8.1%, 7.0%), compared to USFS lands (4.2%, Fig. 6B).

Large and giant trees are less likely to burn than small trees during a high-severity fire and are a forest structure indicator of wildfire resilience (Table 2). National forests and tribal forests have comparatively high proportions of large and giant trees (33.9% and 33.7%, respectively), with low proportions of small trees (40.8% and 41.8%, respectively; Fig. 6C). In private corporate forests, by contrast, the area of large and giant trees (16.3%) is half that in USFS and tribal forests, and small trees are dominant (54.4%); structural variability among private owners is high, however (Appendix 1).

Fig. 6. Forest structure indicators of wildfire-resilience by ownership group category (U.S. Forest Service [USFS], private corporate, and tribal). Results are for forested areas with trees > 25.4 cm diameter at breast height only, so percentages do not sum to 100. (A) Frequent-fire forest potential vegetation type (PVT) area as a proportion of the forested PVT area of the ownership group. These correspond to PVTs 1–5 (alpine/high elevation, lodgepole pine, moist mixed conifer, dry mixed conifer, and ponderosa pine, respectively). (B) Ecological states (early successional forest structure vs. resilient, older forest structure) as a landscape proportion (%) of frequent-fire PVT area. (C) Tree size class as a landscape proportion (%) of frequent-fire PVT area. (D) Canopy-cover class as a landscape proportion (%) of frequent-fire PVT area. For (B–D), the landscape pertains to frequent-fire PVT area (PVTs 3–5).



Canopy cover class, a second indicator of wildfire resilience, also varies among ownerships (Fig. 6D). Open-canopy forest is relatively resilient to wildfire compared to closed-canopy forest owing to more widely spaced trees and less ladder fuel. In national forests, the proportion of closed-canopy forest is high (42.9%), and open-canopy forest is low (25.9%), although proportions vary between DNF and FNF (Fig. A1.1 in Appendix 1). Private corporate forestland has a similarly high proportion of closed-canopy forest (41.5%), but a moderate to high proportion of open forest (33.2%). In tribal forests, the proportion of closed-canopy forest is comparatively low (32.0%), and open forest is moderate to high (32.0%).

DISCUSSION

We found that informal institutions (e.g., culture, knowledge system, fire paradigm) and institutional history play roles in wildfire management adaptation (changes in forest fuel treatment, harvest fuel treatment, and wildfire incident response) through interactions with formal institutions (e.g., policy, law) because of effects on managers' decision-making flexibility when responding to ecological feedbacks. We also found that wildfire-resilient forest

structure varied by ownership group. We attribute this variation to institutional dynamics associated with each group, all else being equal. We next discuss the evidence supporting these findings.

Role of wildfire formal and informal institutional evolution on management adaptation vs. stasis

Our results from the eastern Oregon Cascades CHANS demonstrate the influence of wildfire law and policy evolution on management adaptation. For USFS and tribal ownerships, the passage of the *Healthy Forest Restoration Act* and related federal directives during stages III and IV spurred managers to treat forest fuels with mechanical techniques and prescribed burns, which was a management shift compared to earlier periods (Table 4). Our results also suggest that disparate institutional trends can inhibit cohesive broad-scale, cross-ownership adaptation. For private corporate owners, wildfire policy and law have been comparatively static since stage I (post-2010 policy developments notwithstanding, e.g., 2014 Oregon Regional Solutions Participation Plan), and consequently, management adaptation trailed that of USFS and tribal counterparts. Our results correspond with the resource management principle that policy and law drive land-manager decisions (Dana and Fairfax 1980, Cabbage et al. 1993). This assumption regarding the policy–behavior linkage consequently structures many agent-based model frameworks (e.g., Bolte et al. 2006, Spies et al. 2017).

Probing deeper, our results also show that informal institutions (cultural norms, knowledge system and fire paradigm, forest management ideals, and economic ideals) may exert powerful influences on managers' flexibility to respond adaptively to hazard change. Informal institutions are important in that they seem to operate together with formal institutions as a set of influences on managers' flexibility to adopt adaptive practices. On the DNF for instance, the shifts in knowledge system (from a conventional science fire paradigm toward an ecosystem science paradigm) and cultural norms (from risk aversion toward paradigm questioning) expanded the range of organizationally viable options regarding wildland fire use, as demonstrated in a 1978 Environmental Assessment (DNF-WNF 1978):

It is important...to note that the objective...is "to manage natural fire" and not repress it entirely as in the past. The road ahead is not going to be easy... But as we cautiously allow nature to do her original job of slash treatment, we must remember that in the first few years she will have the added responsibility of correcting our past mistakes. The predicted long-term effects of [fire reintroduction] on the fuels of this area are very favorable.

The DNF management team's decision to adopt an adaptive response (allow wildland fire use, introduce prescribed burns) grew out of reinforcing developments among informal and formal institutions. We conclude that in frequent-fire CHANS, wildfire management adaptation is apparently structured by the interaction between developments in formal and informal institutions, not formal institutions alone. Our findings demonstrate that the complexity of institutional influences on decision making that has been advanced theoretically (Helmke and Levitsky 2004) and in distinctly political settings (Bratton 2007) also applies to land management decision making.

Our results also suggest that flexibility to respond adaptively to wildfire hazard change depends on synchronous evolution of

informal institutions in tandem with formal institutions. In the DNF for instance, synchronous developments between the dominant knowledge system and fire paradigm and formal agency-wide USFS policies (i.e., 1977 modification of the 10:00 A.M. Control Policy) engendered a comparatively flexible decision-making space in which managers could adapt to growing fuel hazard. Elsewhere, social science research has found a similar relationship: the condition of alignment (or misalignment) between federal or state policy development and local culture influences whether or not innovative behavior is implemented (Steelman 2010). The probability of innovation and adaptive response to changing conditions increases when federal (“top-down”) formal rules and local (“bottom-up”) informal rules are “mutually supportive” (Steelman 2010:13). Our study reveals a related finding: the timing (i.e., synchronicity) of formal and informal institutional evolution matters to manager flexibility. By contrast, in conditions of asynchronous formal-informal institutional evolution, adaptive response to wildfire hazard condition is more limited, as demonstrated by the comparatively moderate adaptation of the tribal ownership during the reevaluation and redirection-reorganization stages (i.e., adoption of forest fuel prescribed burns and mechanical treatments, but not wildland fire use; Table 3). Breaking out of the constraints imposed by the wildfire paradox, therefore, seems to require the synchronous evolution of adaptive norms, knowledge system, and forestry and economic ideals in tandem with promulgation of adaptive law and policy.

Our results also suggest that the evolution of cultural norms regarding collaboration within the management organization and stakeholder communities can expand decision-maker flexibility to implement new laws and policies. For instance, recent fire-prone forest restoration legislation (e.g., *Healthy Forest Restoration Act*) directs DNF, FWNF, and WSR land managers to treat forest fuels. In practice, however, community support influences flexibility to implement treatments (Ryan et al. 2013) and is structured through norms of collaboration and learning network approaches. One interviewee explained:

We've used the Fire Learning Network for almost a decade now to have those broader public community dialogue[s] about the role of fire on the landscape [regarding] what we want our forest to look like over time. I think that's one of the reasons that [enables] the vegetative treatments that we do on the landscape here on the Deschutes National Forest. We get a lot of community support for what we're doing.

The importance of agency–community collaborative arrangements in forging broadly supported decisions on contentious topics has been demonstrated in forest ecosystems across the western United States (Wondelleck and Yaffee 1994). Our findings suggest that collaborative cultural norms are an integral element of such arrangements, possibly because of their capacity to shore up cross-ownership cooperation and trust, which are influential factors in wildfire decisions (Fischer and Charnley 2012). For land managers, the effects of new adaptive laws and policies may be leveraged by complementary investment in building collaborative norms.

Role of institutional history on management adaptation vs. stasis

Our results also indicate that institutional history has influenced (e.g., constrained) wildfire management evolution and adaptation and that, in multiownership landscapes, managers confront diverse constraints on adopting adaptive practices. Institutional legacy effects on management flexibility exist for two reasons. First, institutions are recursive in that they are both agents of influence and acted upon through their interactions with society, resulting in coevolution into the present. For instance, past forest policies shaped cultural norms, which subsequently influenced later policies. Second, institutions are culturally constituted, that is, culture influences how social groups (e.g., agencies) shape behavioral rules (Folke et al. 1998, Petty et al. 2015), which may become ingrained over time. In addition, preference for the status quo in the face of uncertainty may partially contribute to the influence of institutional history.

Among federal land management agencies, for example, “entrenched disincentives” such as intolerance for management errors contribute to the insufficient reform in wildfire management (North et al. 2015) despite policy evolution (Busenberg 2004). Our results provide insight into the historical roots of these contributors to the wildfire paradox. The legal, policy, and informal institutional developments of the establishment and systemization-centralization stages laid the groundwork for current entrenched disincentives to management adaptation. In the DNF and FWNF organizations, historical laws and policies to promote sustained yield (1924 *Clarke-McNary Act*, 1944 *Sustained-Yield Management Act*) coevolved with the community economy, which ingrained the ideal of community economic stabilization (Cowlin and Moravets 1938). For managers, these agency-community interrelationships engendered planning-based, risk-averse cultural norms, as illustrated by historical DNF fuel hazard maps (Fig. 4). Though production volume targets have changed, fire managers continue to operate in a risk-averse culture (Charnley et al. 2015) and are charged to maintain forest productivity, among other ecosystem services, to benefit forest communities (Smith et al. 2011). Despite recent policy developments, the flexibility to use the full array of restoration tools, potentially including wildland fire use in some areas, is constrained by coevolved norms (e.g., risk averse cultural norm), which became ingrained over time (Table 6). Regarding wildland fire use however, we note that federal land management agencies continue to search for the appropriate concept, assess its feasibility, and grapple with barriers to implementing this management tool (Doane et al. 2006).

The WSR case also demonstrates the legacy effects of institutional history on current wildfire management decision making. Similar to the USFS case, institutional history appears to have constrained WSR manager adaptive flexibility, although for differing social historical reasons, e.g., legacies of historical tribal forest policy, community economics, and forest management. Tribal trust doctrine (1831) established a unique institution among land management agencies: a fiduciary responsibility to manage resources for the benefit of Indian tribes. This doctrine and the laws that followed it (1910 *Indian Omnibus Act*, 1934 *Wheeler-Howard [Indian Reorganization] Act*) underpinned the ideal of community economic stabilization. Early to mid-20th century managers' conceptions of economic self-sufficiency assumed that tribes would adopt the western extractive economic

worldview and abandon traditional practices and economic structures (Steen-Adams et al. 2010). They therefore interpreted these historical laws and policies as calling for intensive forest management and fire suppression to enable economic self-sufficiency through timber production, which contributed to unanticipated changes to forest structure and wildfire hazard (Weaver 1957c, 1965). As interconnected system factors played out, e.g., historical policies, growing community economic dependence on forest resources, and forest structural changes, managers harvested at an unsustainably high rate (CTWSRO 1993). For current managers, the interaction of economic history effects, specifically, continued importance of timber revenue to the WSR's economy (CTWSRO 2003), and legacy effects of past heavy harvests (1940s–1980s), driven by past managers' interpretation of tribal trust doctrine, has resulted in constrained fire management options. Consequently, WSR land managers are in a bind: forest fuels and activity fuels are treated, yet all wildfire incidents are suppressed, contributing to forest fuel accumulation, and harvest practices that can reduce forest resilience are employed (clearcuts in frequent fire forest zones).

The private corporate forest ownership group demonstrated a third combination of factors involving institutional history that influence wildfire management decision making. This case highlights the mutually reinforcing role of management goals, legal and interorganizational history, and informal institutions (fire management paradigm) on wildfire management. As an ownership group, practices have been relatively static (Table 4). In general, throughout the 1905–2010 study period, suppression of fire incidents has served as the primary tool to manage fire hazard, rather than as one of several strategies available to deploy. One factor that influences this suppression-focused approach is the goal (and need) to generate profit: property loss to wildfire would impair this goal. Another factor is the legacy effect of legal and interorganizational history. Early state laws set a precedent mandating the State Forester and associated designates to suppress fire to protect private property (e.g., 1911 *Oregon Forest Fire Law*, 1913 *Oregon Fire Patrol Act*). Equally important, early fire laws reinforced the interorganizational interdependence between private corporate owners and the state. Forest owners would generate economic productivity, forestry jobs, and tax revenue, while the state would provide forest protection: “every stick of timber in Oregon will be used to produce a field for labor and add to our prosperity... if it is not burned up” (1925 *Oregon Forest Fire Law*). Recent legislation upholds this legal-interorganizational history legacy: “preservation of forests... through [wildfire] prevention and suppression...[is] the public policy of the State of Oregon” (2009 *Fire Protection of Forests and Vegetation*). Third, the fire paradigm and knowledge system within which current managers make decisions is an outgrowth of the conventional science paradigm of long-established Forest Protection Associations, and ultimately, of early 20th century forest patrols. In sum, these three factors, i.e., the goal to generate profit, the legal and interorganizational legacies of forest industry-state interdependence, and the continuing conventional science fire paradigm, reinforce one another, generally maintaining the status quo rather than promoting adaptation.

Given the above, we note that there are institutional developments relevant to private corporate owners currently in progress. The Fire Program of the 2014 Oregon Regional Solutions Protection

Participation Plan acquires federal grants and provides forest fuel treatment guidelines, particularly in relation to air quality (ODF 2014). The growing effort to identify funding sources to treat forest fuels (e.g., Community Wildfire Protection Plans) may address a key economic constraint that private corporate owners confront. In the future, this effort may promote expanded adoption of adaptive practices and increase the land area with wildfire-resilient forest structure.

In sum, a main management insight of our retrospective analysis is that legacy effects of heterogeneous laws, policies, and informal institutions can comele across the forest landscape owing to diverse and semi-independent institutional histories. Consequently, the factors that contribute to the wildfire paradox are heterogeneously distributed, contributing complexity to coordination initiatives. The three ownership groups studied here have contended with diverse institutional legacy effects on management adaptation (USFS: entrenched disincentives, associated with cultural norms of risk aversion and a forest economic ideal of community economic stabilization; tribal: legacies of tribal trust doctrine, community economic stabilization, and past forest harvest; private corporate: private property protection mandate coupled with conventional fire paradigm). Institutional history can thus point to the roots of diverse constraints that operate in multiownership landscapes. Historical awareness may also point to opportunities for collective action rooted in historic cooperative, cross-ownership wildfire institutions and management practices such as those that prevailed during stage II in the study area.

Sources of forest structure variation among large landowner groups

Our ecological analysis of the Oregon multiownership frequent-fire system found that resilient forest structure indicators currently vary among large ownership groups. Overall, wildfire resilience was lowest on private corporate forests, highest on USFS forests, and intermediate on tribal forests. A related study found that a main factor that contributed to current cross-ownership structural variation is management history variation (Charnley et al. 2017). Our study augments this finding by highlighting the role of variation in historical stage chronologies among ownership groups (Table 1). The timing of management stage transition differs between ownership groups. On USFS and tribal lands, the shift between systemization-centralization stage (stage II) institutions and practices to those of the reevaluation stage (stage III) occurred in the 1970s. By contrast, on private corporate lands, the shift occurred in the 1990s. This two-decade time difference matters to forest conditions. During this time, DNF, FWNF, and WSR organizations undertook the multistep, time-intensive process of adjusting to developments in federal policy, law, and informal institutional norms with wildfire management change, eventually contributing to comparatively higher resilience. By contrast, private corporate owners (as a group) began to reevaluate wildfire management formal and informal institutions and practices of the systemization-centralization stage only relatively recently (roughly two decades ago), which is a relatively short period for the complex process of adaptations in interrelated policies, laws, cultural norms, related informal institutions, and management to develop and eventually influence wildfire resilience.

Developments in wildfire formal institutions that have occurred since the 1970s (reevaluation and redirection-reorganization stages) are important contributors to the comparatively high resilience of USFS forests. In 1989, the USFS Manual directed managers to implement a new prescribed burn policy. In the 1990s, new policies directed against harvest of large trees owing to concerns to protect old growth (the “21-inch rule” of the Eastside Forest Ecosystem Health Assessment, Powell 2013). Beginning in 1995, federal wildfire policy directed integration of “fire as a critical natural process” into management plans (USDI-USDA 1995), and by 2000, treatment of forest fuels (USDA-USDI 2000, Stephens and Ruth 2005). Equally important, Congress appropriated fuel treatment funding, which expanded manager flexibility to shift away from past suppression-based wildfire management (Ryan et al. 2013). Over time, USFS managers shifted forest fuel practices from no treatment (stages I and II) to prescribed burn (stage III) and then to both mechanical and prescribed burn treatments (stages III and IV) and reduced harvest of large trees.

We further attribute the comparatively high resilience of USFS forests to synchronicity between informal and formal institutional evolution. For example, between stages II and III, the USFS knowledge system shifted from conventional science to adaptive ecosystem management (Gray 2000); cultural norms shifted from planning-centric, hierarchical, and risk-averse management to collaborative management; and forest management ideals shifted from continuous production and sustained yield to diverse benefits and ecosystem services. These changes reinforced the formal institutional changes. The synchronicity of formal-informal institutional evolution likely augmented USFS manager flexibility to respond to forest fuel accumulation with thinning and prescribed burn treatments, in turn contributing to greater forest resilience to wildfire.

Tribal (WSR) forest structural resilience presents an illuminating comparison to USFS and private corporate forests. Since stage III, WSR wildfire hazard management decisions have generally been influenced by the same recent federal policies that influence USFS managers owing to USDA-USDI coordination. Consequently, tribal managers, like USFS managers, currently apply prescribed burns and mechanical thins to treat forest fuels. In addition, interviews suggest that historical (1950s–1970s) experimental application of prescribed burns to WSR stands promoted a culture of manager receptivity to this tool. Regarding size-class harvest restrictions, the WSR Integrated Resources Management Plan (CTWSRO 2003) directs managers to maintain a diversity of age and size classes, retaining larger trees in specified zones. Therefore, recent federal and WSR policy developments may partially account for the comparatively high proportion of large trees and intermediate level of wildfire-resilient forest structure.

Our results also highlighted the constraints posed by institutional and management legacies on current WSR decision making despite recent policy developments. During stage II, managers selectively harvested large ponderosa pines and suppressed fire over a prolonged period relative to the fire-recurrence interval. This management system converted the forest composition, by which a shade-tolerant Douglas fir overstory outcompeted shade-

intolerant pines, and increased stand density (Weaver 1958, CTWSRO 2003). WSR managers then began to apply even-aged harvests to the converted stands (e.g., Douglas fir, ponderosa pine) to fulfill the tribal trust doctrine to support an integrated reservation forest-mill economy (Weaver 1965). Current managers continue even-aged management in these zones, contributing to the high proportion of early seral-stage forest cover.

Regarding the comparatively lower (on average) wildfire-resilient forest structure of private corporate lands, our analysis revealed the role of relative timing, previously discussed, and of institutional history. However, forest structure of private forests varies widely (Appendix 1) partly because of the diversity of informal institutions, for instance, short-term vs. long-term economic ideals. Over the 1905–2010 study period, the pace of policy adaptation relevant to private corporate owners (i.e., state policies) has trailed behind those of USFS and tribal owners, resulting in relatively limited current policy adaptation to changing hazard conditions. Policies governing private owners generally prioritize fire suppression rather than fuels reduction to manage fire hazard (ODF-INR 2005). Until recently (ODF 2014), forest fuel treatment directives have applied to USFS and tribal forests but not to private corporate forests, other than those that are designated as forestland-urban interface areas under the *Oregon Forestland-Urban Interface Protection Act* (<https://www.oregon.gov/ODF/Fire/Pages/UrbanInterface.aspx>). Underlying these comparatively less-adaptive policies is legal history. State legal history, which mandates protection of forest private property, imposes challenging practical constraints on the possibility of shifting policy away from the current suppress-all-fires approach.

A further contributor to the private corporate group’s comparatively lower forest resilience is the funding disparity at federal and state levels: federal and tribal landowners have access to fuel treatment funding through U.S. Congressional appropriations, but private corporate owners do not (unless included in Community Wildfire Protection Plans). Funding availability is an important factor that affects institutional capacity to influence wildfire-resilient forest structure (Ryan et al. 2013). Thus, corporate owners, who have generally lacked public funds to treat forest fuels, face a distinct constraint relative to other large landowners, a private-public wildfire management disparity detected by other research in the Oregon study area (Charnley et al. 2017). Moreover, cultural norms among private owners are generally averse to employing prescribed fire to reduce forest fuels (Charnley et al. 2017). One approach to promote an adaptive shift toward mechanical treatment of forest fuels would be to create a state- or federal-level funding structure to help offset treatment costs, justified by the argument that wildfire hazard management is a public good (Busby and Albers 2010).

CONCLUSIONS

We constructed social-ecological histories (1905–2010) of USFS, private corporate, and tribal landowners and examined wildfire-resilient forest structure in a multiownership, frequent-fire CHANS in Oregon. Our main goals were to generate insights regarding institutional influences and constraints on wildfire management adaptation, their effects on current wildfire-resilient

forest structure, and how the wildfire paradox has developed in multiownership landscapes. Our findings have several implications for efforts to promote broad-scale, coordinated wildfire management across ownerships.

We found that among large landowners in Oregon's eastern Cascades, wildfire management formal and informal institutions gradually converged over several decades (1905–1930s), resulting in general institutional coordination during the 1940s–1970s to meet shared forest protection goals. Historical state and federal policies and laws, including fire suppression funding mechanisms and associated administrative structures, were coordinated. In addition, many informal institutions were held mutually among ownership groups. In combination, formal and informal institutions coalesced to fulfill the societal need for wildfire management for a time while simultaneously laying the foundation of the current wildfire paradox, which was an unanticipated consequence.

In contrast, current wildfire policies are comparatively disparate and disconnected between the federal (USDA-USDI) and state (private ownership relevant) levels, contributing to more forest fuel treatment and more resilient forest structure on USFS and tribal lands than in private corporate forests. Nevertheless, our historical findings suggest that coordinated, cross-ownership wildfire management may be promoted by: (1) re coordinating federal and state laws and funding mechanisms associated with wildfire risk reduction; and (2) developing informal institutions of collaboration, potentially via social networks (Fischer and Jasny 2017). Private corporate owners are currently less engaged in coordinated, cross-ownership management with the USFS than they were historically, which was aided by collaborative policies, associated funding, and informal institutions embedded in organizations. This finding suggests an important group to reengage, potentially building on the state's (ODF's) historical (and reemerging) organizational leadership role.

We also found that time lags play a critical role in wildfire management behavioral adaptation. Historically, forest managers developed institutions and management behaviors to promote desired ecological conditions and community economic benefits through sustained yield timber production. These institutions and behaviors generated unanticipated, undesired ecological feedbacks, despite some benefits. A long time lag occurred until decision makers recognized these ecological signals, and an even longer time lag occurred until they adapted existing institutions and developed new ones in response. Informal institutions played a key role in influencing how, and how quickly, these responses took place among ownership groups, affecting manager flexibility to respond to hazard change and contributing to variation in management adaptation.

A related finding is that synchronicity in the evolution of formal and informal institutions may influence the flexibility to implement adaptive practices. By contrast, asynchronous institutional evolution may constrain adaptation. Despite significant wildfire policy developments, the evolution of informal institutions embedded in organizations often lags behind the formal ones owing to their complexity, thereby constraining adaptation and reducing wildfire resilience. This finding points to the need for attention to complementary informal institutions (cultural norms, knowledge system, forest production ideal, and

economic ideal) to promote synchronous development with that of formal institutions. This expanded approach may shorten response times to undesired ecological feedbacks and consequently shorten CHANS time lags. The capacity to respond adaptively to increased wildfire hazard depends on the flexibility to implement existing policy fully (Steelman and McCaffrey 2011); thus, interventions that target informal institutions may be more effective than law or policy revision at times.

Much attention has focused on federal forests as the locus of the wildfire problem and on the institutions that enable or constrain federal managers in addressing it. In multiownership settings, however, initiatives for cohesive, broad-scale wildfire management depend on recognizing the diversity of institutions that promote (or constrain) managers' flexibility. For example, tribal forest managers in Oregon's eastern Cascades confront distinct constraints compared to their USFS and private corporate counterparts. Recent (post-1995) federal wildfire policies, which span USFS and tribal lands through a shared federal structure, would seem to enable similar adoption of adaptive practices. However, current tribal managers are comparatively constrained, partly because of institutional legacy effects. For instance, the interpretation of tribal trust contributed to a forest resource-dependent economic structure, remnants of which have limited the transition away from a conventional fire paradigm. Policies and funding to reduce historical tribal community dependence on timber revenue may loosen current wildfire management constraints. In multiownership landscapes, recognizing and engaging with institutional history and informal institutions, as interacting factors with current formal institutions, can promote goals to implement cohesive, broad-scale wildfire management across ownership boundaries.

Finally, a historical perspective can help explain why current ecological conditions such as wildfire-resilient forest structure often vary at a broad spatial scale and across ownerships. Trends in institutional factors often vary among ownerships, contributing to variation in management practice and, consequently, forest structure. Looking forward, the public will have to decide the acceptable level of wildfire risk relative to its social, economic, and ecological costs. Learning from past actions, both successful and unsuccessful, to address these challenges may help to develop interventions that meet current and future management goals.

Responses to this article can be read online at:

<http://www.ecologyandsociety.org/issues/responses.php/9399>

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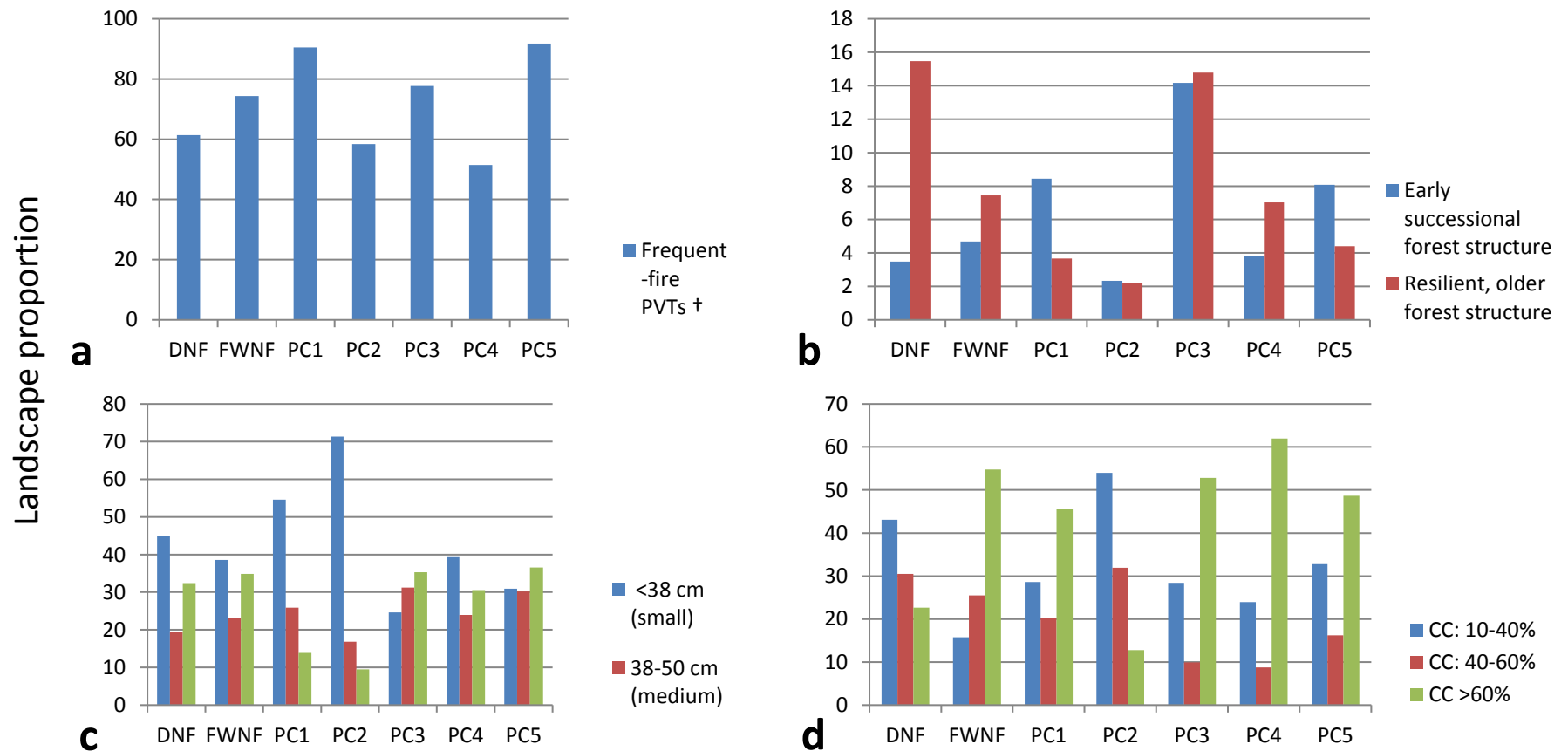
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Appendix 1. Within-ownership variation among USFS and private corporate ownership groups regarding forest structure indicators of wildfire resilience. X-axis abbreviations reference the following owners: DNF: Deschutes National Forest; FWNF: Fremont-Winema National Forest; PC 1, PC 2, PC 3, PC 4, PC 5: private corporate owners that owned at least 10,000 hectares of land in study area.



[†] Frequent-fire forest: PVT 3 (Moist mixed conifer), PVT 4 (Dry mixed conifer), PVT 5 (Ponderosa pine)