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REVIEW ARTICLE

Restoring fire-prone Inland Pacific landscapes: seven core principles

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Abstract
Context More than a century of forest and fire management of Inland Pacific landscapes has transformed their successional and disturbance dynamics. Regional connectivity of many terrestrial and aquatic habitats is fragmented, flows of some ecological and physical processes have been altered in space and time, and the frequency, size and intensity of many disturbances that configure these habitats have been altered. Current efforts to address these impacts yield a small footprint in comparison to wildfires and insect outbreaks. Moreover, many current projects emphasize thinning and fuels reduction within individual forest stands, while overlooking large-scale habitat connectivity and disturbance flow issues.
Methods We provide a framework for landscape restoration, offering seven principles. We discuss their implication for management, and illustrate their application with examples.
Results Historical forests were spatially heterogeneous at multiple scales. Heterogeneity was the result of variability and interactions among native ecological

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patterns and processes, including successional and disturbance processes regulated by climatic and topographic drivers. Native flora and fauna were adapted to these conditions, which conferred a measure of resilience to variability in climate and recurrent contagious disturbances.

Conclusions To restore key characteristics of this resilience to current landscapes, planning and management are needed at ecoregion, local landscape, successional patch, and tree neighborhood scales. Restoration that works effectively across ownerships and allocations will require active thinking about landscapes as socio-ecological systems that provide services to people within the finite capacities of ecosystems. We focus attention on landscape-level prescriptions as foundational to restoration planning and execution.

Keywords Forest and rangeland restoration · Hierarchical organization · Large fires · Patch size distributions · Successional patches · Topographic controls

Introduction

Land management in the Inland Pacific United States (US) faces unprecedented challenges:

- A growing human population that demands contradictory or competing ecosystem services (Krieger 2001);
- Impaired ability of some landscapes to provide these services due to past management (Millenium Ecosystem Assessment 2005);
- Increased exposure to large and often severe disturbances (Schoennagel et al. 2004; McKenzie et al. 2004; Agee and Skinner 2005; Hessburg et al. 2005; Peterson et al. 2005; Miller and Davis 2009; Miller et al. 2009; *cf.* Baker 2012; Williams and Baker 2012; Odion et al. 2014);
- New or alternative ecosystem states following large or severe disturbances (Allen et al. 2010; Odion et al. 2010);
- Decline and extinction of some native plant and animal populations, and increasing invasions by non-natives (Noss and Cooperrider 1994; Reed et al. 2003);
- High uncertainty regarding future effects of climate change (Millar et al. 2007);
- Diminished public confidence in land managers (Duncan et al. 2010; Keiter 2005; Williams and Jackson 2007).

To address these challenges, a new collaborative social contract for federal land management in the West is emerging (Schultz et al. 2012; Butler 2013; Larson et al. 2013; Charnley et al. 2014). Established collaboratives seek to move past once crippling conflicts over natural resource management, forge social consensus around management approaches that can restore or create climate- and fire-resilient landscapes, and improve future options for people (Brown et al. 2004; Cheng and Sturtevant 2012; Charnley et al. 2014; Stephens et al. 2014). To effectively manage landscapes as resilient and adaptable social-ecological systems (Folke et al. 2005; Chapin et al. 2010), collaboratives must work from a solid scientific foundation.

In this review, we present principles from recent landscape science that are relevant to collaborative restoration, to raise the bar for land use planning and management across all ownerships. We emphasize Inland Pacific forests of Washington, Oregon, and California; however, our ideas are useful for landscapes beyond this domain, including the southwestern US and Rocky Mountain regions (Jain et al. 2008; Reynolds et al. 2013). Furthermore, we emphasize management of fire-prone forests, but recognize the importance of other physiognomic types as part of these landscapes, as well as lands intensively used by people.

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Recent research has expanded our understanding of multi-scale heterogeneity in historical fire-prone forests. Fire-prone forests are current or historical dry, mesic, or cold interior forest types that depend on wildfires for regeneration and succession. Heterogeneity resulted from interactions among climate, vegetation, topography, and disturbances that created successional patterns and shaped disturbance regimes to which native flora and fauna are adapted at fine-, meso-, and broad-scales. It evolved dynamically and conferred a measure of resilience to shifts in climate and recurrent contagious disturbances.

Historical context–unintended consequences

For most of the twentieth century, federal land management in the Inland Pacific emphasized wildfire suppression, domestic livestock grazing, and wood production to meet the demands of a growing society (White 1991; Langston 1995; Robbins 1999). Grounded in a utilitarian view of forests, silvicultural methods were devised to grow, harvest, and regenerate trees (Smith et al. 1997). Wildfires were viewed as threatening to people, infrastructure, and the timber supply.

Silviculture and forest management have focused on *stands* as the basic unit of organization (Puettman et al. 2012). *Stands* are defined as contiguous areas of trees with common structural, compositional, and biophysical conditions (Helms 1988; Nyland 2002). Delineation of treatment units, 'operational stands'(sensu O'Hara and Nagel 2013), however, is shaped by added operational considerations including economic viability, road access, property boundaries, logging systems, and harvest scheduling.

These treatment units stood out in marked contrast to historical successional *patches*, which were variably-sized and shaped by the surrounding topography and prior disturbances. Even-aged management within operational stands promoted uniformity of tree conditions (e.g., size, density, species, spacing), while reducing costs of harvest, yarding, and log transportation. Uneven-aged management promoted variable size and age distributions, and often led to multistory structures dominated by shade tolerant species. Harvests of all types generally targeted high volume stands and removed large and old trees of fire tolerant species. Furthermore, prescriptions focused on tree conditions within stands and overlooked the larger scale patterns that emerged from this stand-based management.

Over time, timber harvest altered the size distributions, shapes and spatial arrangements of successional patches, while reducing numbers of large trees. Successional patches that had been historically created and maintained by disturbances (sensu Oliver and Larson 1996; O'Hara et al. 1996), often were fragmented by new patterns arising from stand management (Fig. 1; O'Hara and Nagel 2013). Resulting patterns varied by forest type and management. In cool, mesic mixed-conifer forests, where dispersed clear cuts were emphasized, successional patches were bisected by plantations, which were often smaller by two or three orders of magnitude (Franklin and Forman 1987; Belote and Aplet 2014; Hessburg et al. 1999b, 2000a). In marked contrast, in dry pine and mixed-conifer forests, elective removal of large, fire-tolerant trees and subsequent regeneration and release of shade-tolerant conifers increased the patch size and abundance of dense, multistory forest conditions (Hessburg et al. 1999b, 2000a, 2005; Keane et al. 2002, 2009; Hessburg and Agee 2003; Parsons and DeBenedetti 1979). Fire exclusion allowed these conditions to persist. In many areas, livestock grazing removed fine fuels and reduced fire frequency, further contributing to fire exclusion (Savage and Swetnam 1990; Belsky and Blumenthal 1997). Thus, the pattern observed in modern-day managed pine and mixed-conifer landscapes is largely the result of stand management, roads, livestock grazing, and fire exclusion, which is now being altered by wildfires that often defy suppression efforts during extreme weather conditions (Schoennagel et al. 2004; Naficy et al. 2010; Lydersen et al. 2014).

Stand management and dispersed clearcutting necessitated development of extensive road networks to reach high-value stands (Reeves et al. 1995). The new roads altered local hydrology, increased chronic and catastrophic sedimentation, and reduced floodplain functioning via channelization (Luce and Black 1999; Jones et al. 2000). Roads fragmented aquatic habitats, and created fish passage barriers via crossings and culverts (Bisson et al. 2003; Rieman et al. 2003). Roads were effective fuelbreaks during moderate fire weather conditions; they played a role in spreading invasive plants, and provided access for firefighters (Forman 2003). Roads also disturbed wildlife nesting and denning, and interrupted breeding and dispersal

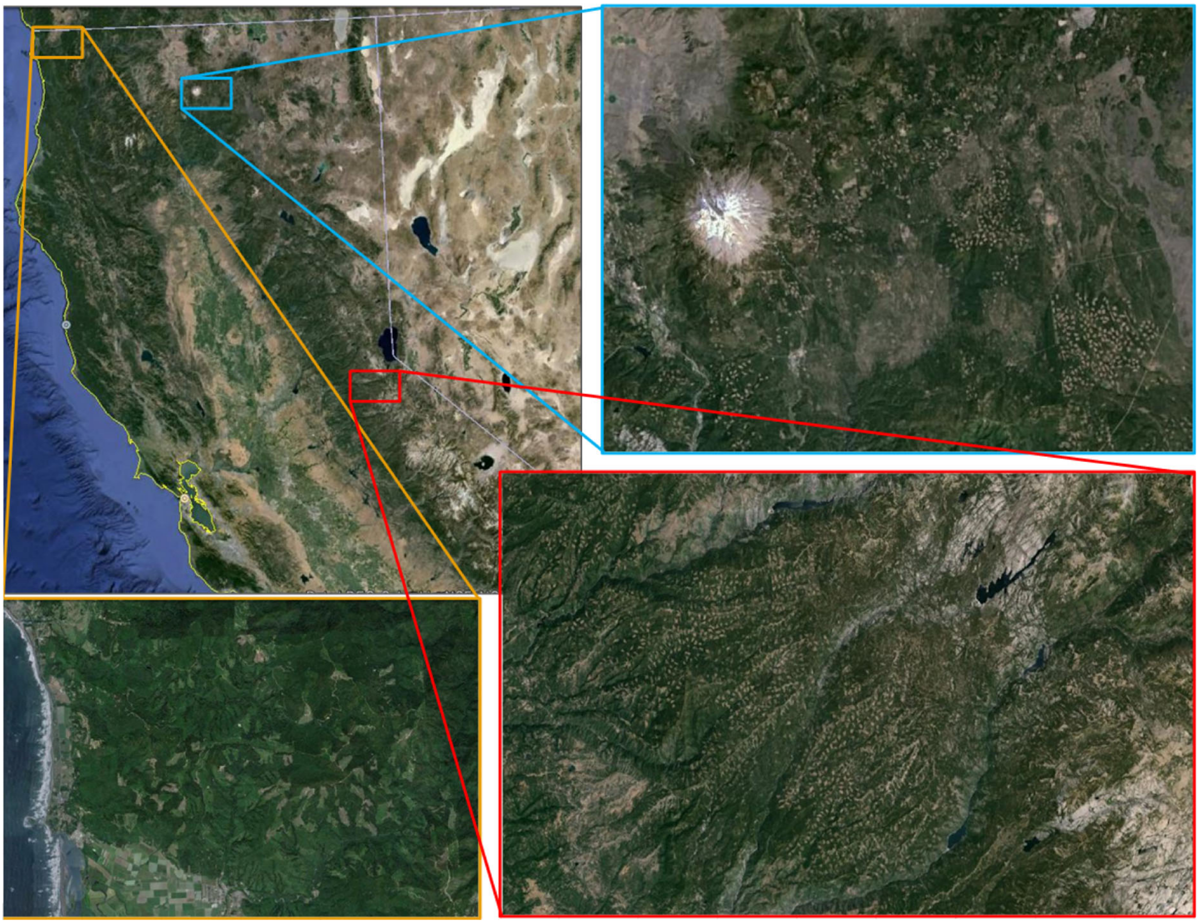


Fig. 1 Fragmentation of the northern California landscape (*upper left*). Shown in inset views are an area east of Mt. Shasta (*upper right*), an area along the northwest coast (*lower left*), and an area along the west slope of central Sierra Mountains (*lower right*). Note the parcelization of the forest landscape by the emplacement of stand management units. All photos are courtesy of Google Earth 2014. Much of the area with recent clear cuts is on private lands

habitat connectivity (Raphael et al. 2001; Gaines et al. 2003).

Today, successional patchworks of many forest landscapes no longer reflect a tightly linked relationship with their natural disturbance regime calling for restoration of many watersheds and lands (Keane et al. 2009; Wiens et al. 2012; Moritz et al. 2013). Instead, new fire, insect and pathogen disturbance regimes are driven by past management, a warming climate, and contagious patterns of fuels and hosts (Noss et al. 2006), fostering increased numbers of larger and more severe disturbances than occurred historically (McKenzie et al. 2004; Hessburg et al. 2005, 2013; Miller and Davis 2009). Predicted changes in the climate could exacerbate these trends (Millar et al. 2007; Allen et al. 2010; Stephens et al. 2013).

Moving from stands to landscapes: core principles and management implications

Re-purposing past approaches to forest management will not address the socio-political and ecological challenges that lie ahead (Lertzman and Fall 1998). Many ecologists, managers, and policy-makers are calling for restoration of many watersheds and landscapes (e.g., see Lertzman and Fall 1998; Bosworth 2006; Noss et al. 2006; ISAB 2011; Franklin and Johnson 2012; North 2012; North et al. 2012a; Franklin et al. 2014; Stephens et al. 2014). For example, the federal Forest Landscape Restoration Act of 2009 called for “collaborative, science-based ecosystem restoration of priority forest landscapes.” Proposals for landscape-scale restoration have been

Box 1 Seven core principles and their planning and management implications

Principle 1: Regional landscapes function as multi-level, cross-connected, patchwork hierarchies.

Implication: Conduct planning and management at appropriate scales to effectively restore multi-level landscape patterns, processes, and dynamics.

Principle 2: Topography provides a natural template for vegetation and disturbance patterns at local landscape, successional patch, and tree neighborhood scales.

Implication: Use topography to guide restoration of successional and habitat patchworks.

Principle 3: Disturbance and succession drive ecosystem change.

Implication: Move toward restoring natural fire regimes and the variation in successional patterns that supported them so that other processes may follow.

Principle 4: Predictable patch size distributions historically emerged from linked climate-disturbance-topography-vegetation interactions.

Implication: Move toward restoring size distributions of historical successional patches and allow changing climate and disturbance regimes to adapt them.

Principle 5: Successional patches are "landscapes within landscapes".

Implication: In dry pine, and dry to mesic mixed-conifer forests, restore characteristic tree clump and gap variation within patches.

Principle 6: Widely distributed large, old trees provide a critical backbone to dry pine and dry to mesic mixed-conifer forest landscapes.

Implication: Retain and expand on existing relict trees, old forests, and post-disturbance large snags and down logs in these types.

Principle 7: Land ownership, allocation, management and access patterns disrupt landscape and ecosystem patterns.

Implication: Work collaboratively to develop restoration projects that effectively work across ownerships, allocations, and access needs.

developed from the Pacific Northwest to the northern Rockies, Sierra Nevada, and the Southwest. However, to be credible, these efforts will need an operational framework based on multi-scale planning and adaptive management, multi-partner and interdisciplinary collaboration, and core ecological principles that reach across scientific disciplines (Grumbine 1994).

Here, we focus attention on anunderutilized forest management concept: *the landscape prescription.* Scientifically grounded landscape prescriptions are needed to create habitat and successional patterns at local and regional landscape scales that move landscapes towards conditions that confer climate and disturbance resilience, while creating functional, well-connected habitat networks for a broad array of native aquatic and terrestrial species. A landscape prescription can provide clearly articulated restoration objectives, target ranges for both total area (proportion of landscape) and patch size distributions of successional and habitat types, and specific guidance on how and where to adjust the spatial arrangement of patches (Perry et al. 2011; North et al. 2012b; Hessburg et al. 2013; Perera et al. 2004).

Resource managers and stakeholders need a common basis to identify long-term objectives for restorative landscape management. Here, we offer seven principles and we use them to construct a forward-looking framework for management of fire-prone interior forest landscapes. We present these principles to help land managers and partners in the Inland Pacific move ahead with effective landscape restoration. The management implications we discuss for each principle can be applied in forest and project planning, designing treatments, monitoring, and collaborative learning (Box 1).

Core principles

Principle 1

Regional landscapes function as multi-level, cross-connected, patchwork hierarchies (O'Neill 1986; Urban et al. 1987; Wu and Loucks 1995), with patterns[1] and processes[2] that interact across spatial scales(Holling 1992; Wu and David 2002; Peters et al. 2004; Falk et al. 2007).

[1] For example, successional or habitat conditions, surface and canopy fuels, tree mortality, fire severity patterns.

[2] For example, hydrologic and nutrient cycles, energy flows, and vegetation succession and disturbance dynamics.

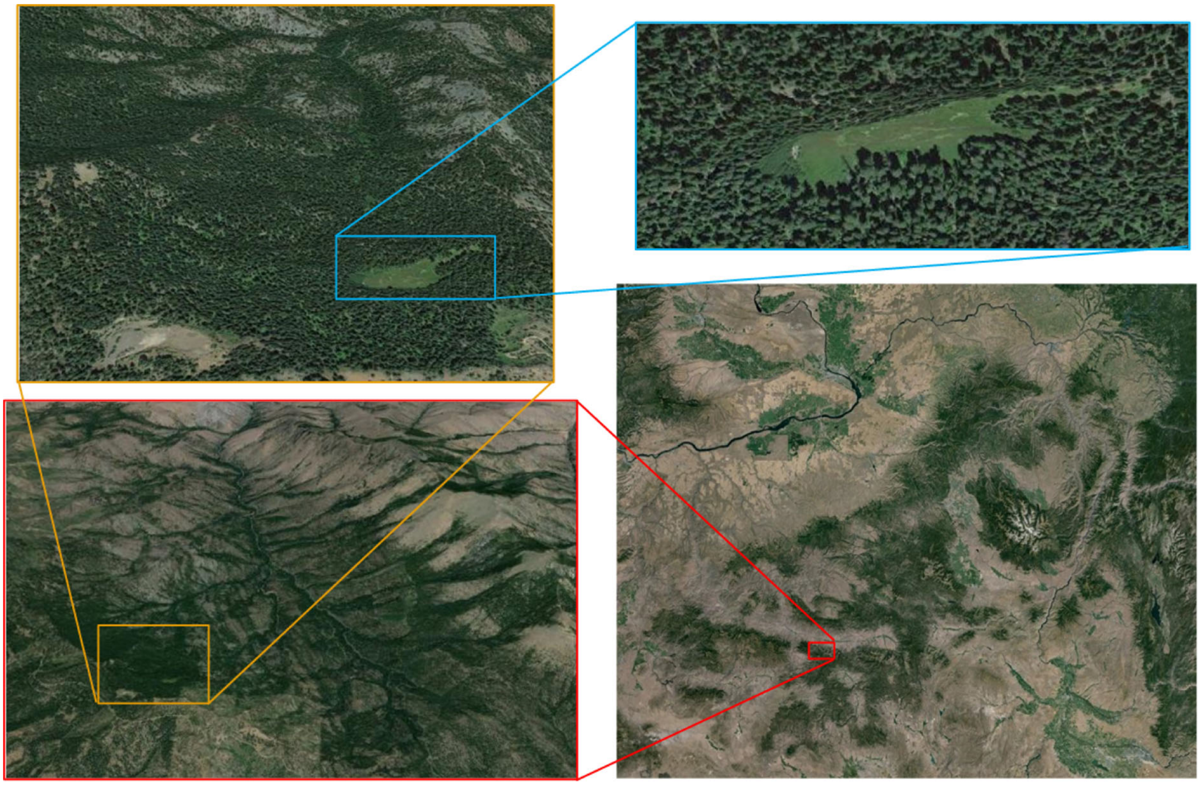


Fig. 2 Landscapes exist within landscapes and there are cross-connections between levels. Shown are the Blue Mountains of northeastern Oregon, USA (*lower right*); the Fields Creek watershed (*lower left*); a patch of headwaters' mixed-conifer forest (*upper left*) in upper Fields Creek, and an individual meadow patch embedded within the mixed conifer patch. Note that all levels exhibit pattern heterogeneity, which influences cross-scale species movements, habitat connectivity and permeability, and disturbance flows. All photos courtesy of Google Earth 2013

We identify four levels of organization, but our framework can accommodate any number (Fig. 2). At the highest level, we identify *ecoregions* and *eco-subregions* (Fig. 3, 100,000's to 1,000,000's of ha; e.g., the Blue Mountains of eastern Oregon, or the Sierra Nevada Foothills of central California). Ecoregions are unique physiographic domains; their seasonal temperature, precipitation, and solar regimes, coupled with unique biotic assemblages, geology, and landforms, yield distinctive lifeform and successional patterns, and disturbance regimes (Küchler 1964; Hessburg et al. 2000b; Hargrove and Hoffman 2004). Ecoregional landscapes comprise *local landscapes* (Fig. 2, 10,000's to 100,000's of ha); groups of 10- or 12-digit hydrologic units [5th or 6th code watersheds and subwatersheds in the NHD watershed hierarchy (http://nhd.usgs.gov/)] may be used. As local landscapes, watersheds and groups of subwatersheds represent local environmental gradients and logical domains where terrestrial and aquatic ecosystem management issues may be simultaneously resolved. Local landscapes comprise *successional patches,* which may be small (<1 ha) to large (1000+ ha) land areas, often strongly associated with topographic features, whose seral status is created by a dominant disturbance, and whose subsequent development depends on interactions among topographic and edaphic environments, stand dynamics processes, and subsequent disturbances. *Tree neighborhoods* comprise the lowest level of our hierarchy; these areas within successional patches have similar arrangements of individual trees, tree clumps and openings in similar micro-environments (Frelich and Reich 1999; Larson and Churchill 2012).In some dry pine forests, where fine grained disturbances are typical, tree neighborhood characteristics may override any obvious successional patchiness.

Over broad scales, historical successional patterns and disturbance dynamics reflected climatic variability and natural disturbance regimes of the

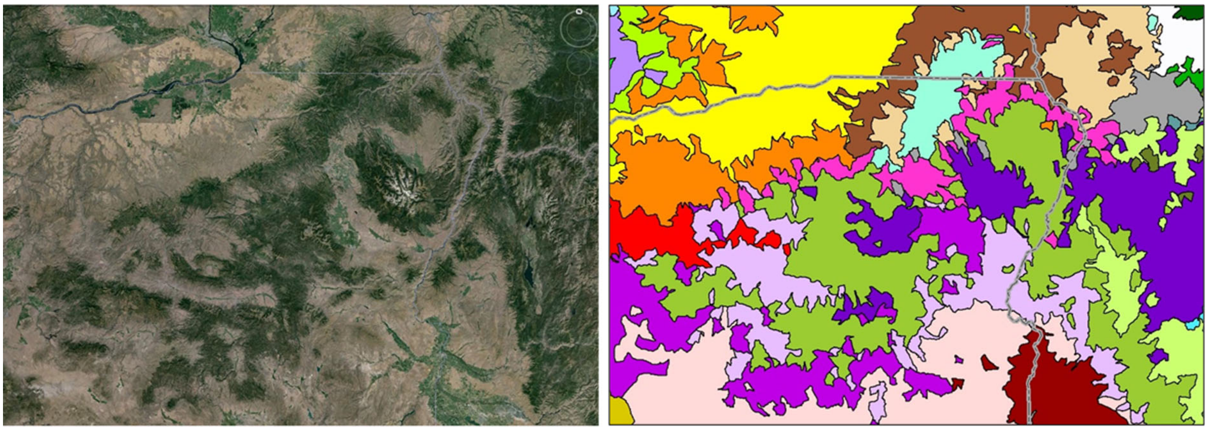


Fig. 3 Ecological subregions (ESRs, *left*) of the Blue Mountains province (*right*). Individual ESRs are unique areas that share a similar climate geology, geomorphic processes, biotic assemblages, and disturbance regimes. ESRs are taken from Hessburg et al. (2000b)

ecoregion (Whitlock and Bartlein 1997; Swetnam et al. 1999; Whitlock et al. 2003, 2010 Keane et al. 2009; Wiens et al. 2012). Within successional patches, tree clump and gap patterns, tree sizes (living and dead), and tree, shrub, and herb species compositions reflected fine-scale productivity, environmental, climatic, and disturbance controls (Larson and Churchill 2012; Churchill et al. 2013; Lydersen et al. 2013).

Hierarchical levels are connected through so-called "top-down" and "bottom-up" controls that operate within and across spatial scales (Wu and Loucks 1995; Wu and David 2002). In our suggested four-level hierarchy, spatial patterns and processes at the scale of the local landscape are partially constrained by the top-down control of climate, geology, landforms, and biota (Fig. 2; Urban et al. 1987; Turner 1989). Patchworks of local landscapes and those operating within successional patches and tree neighborhoods provide critical "bottom-up" control of processes and patterns (Wu and Loucks 1995; Wu and David 2002). For example, patterns of tree species, tree sizes, and tree vigor at tree neighborhood, and successional patch levels can affect patterns of bark beetle induced mortality in local landscapes by influencing host contagion and beetle dispersal. However, these bottom-up controls can be overridden by the top-down influence of extreme climatic events that reduce host vigor or favor beetle survivorship (Bentz et al. 2010).

Implication

Conduct planning and management at appropriate scales to effectively restore multi-level landscape patterns, processes, and dynamics. A reasonable start is to put forest and woodland landscapes on a path to successional patterns and disturbance dynamics that reflect the natural disturbance regimes of regional and local landscapes (Swetnam et al. 1999; Keane et al. 2009; Wiens et al. 2012), and allow the future climate to adapt them. To place landscapes on this path, pattern modifications across scales will be needed in areas where past management alterations are greatest. Management to modify successional patterns should provide a good match to the disturbance ecology and expected future climatic regime of the landscapes in question.

Local landscape prescriptions are also needed that acknowledge constraints imposed by higher levels in the hierarchy that may limit what is achievable. For example, at the ecoregional level, shifting species ranges in response to warming may preclude the persistence of certain tree species at their trailing edge, while others may expand their ranges (Hampe and Petit 2005; Crookston et al. 2010). Thus, landscape prescriptions need to be compatible with the climate at the ecoregion and local landscape levels.

Principle 2

Topography provides a natural template for vegetation and disturbance patterns at local landscape, successional patch, and tree neighborhood scales. Topography modulates broad- to fine-scale patterns of climate and weather, surface lithologies and soils, geomorphic processes, vegetation productivity, and disturbances (Neilson 1986, 1995; Pearson and Dawson 2003). Thus, topography provides an intuitive and persistent physical template for vegetation patterns within regional and local landscapes.

The effect of this template is expressed most strongly in montane forests where ridges and valleys, benches, toe-slope environments, and north- and south-facing aspect patches shaped characteristic patterns and size distributions of historical successional patches (Lydersen and North 2012a; Fig. 4). For example, north-facing aspects and valley-bottoms historically supported many of the densest and most complex (multi-species, multi-aged and multi-layered) mixed-conifer forest conditions (Camp et al. 1997, Olson and Agee 2005; Fig. 5). When fires occurred, these settings typically experienced more severe fire effects than south-facing aspects and ridges. In contrast, south-facing aspects and ridges displayed relatively low tree density, open canopy conditions, and burned more often and less severely (Agee 1993; Habeck 1994; North et al. 2009). Tree-killing bark beetles played a natural role in attacking fire-scarred, weakened, and low vigor ponderosa and Jeffrey pine, Douglas-fir, white fir and grand fir trees, and because of frequent fires, were generally endemic to the landscape. Likewise, defoliating insects frequented denser mixed-conifer patches, especially on north aspects and in valley bottoms (Hessburg et al. 1994).

Implication

Use topography to guide restoration of successional and habitat patchworks. Landscape prescriptions can use topography to tailor species composition, vegetation density, canopy layering, and other structural conditions to edaphic and environmental conditions (Lydersen and North 2012; Merschel et al. 2014). Partitioning the landscape into basic topographic settings, such as valley-bottoms, ridgetops, and south- and north-facing slopes, can be an aid in distributing forest treatments to patch boundaries that are more logical than those based largely on proximity to roads (North et al. 2009, 2012b). Spatially mapped climatic water balance metrics (e.g., actual evapotranspiration and deficit) can be used to further refine and quantify topographic conditions into useful ranges for site potential and species composition determinations, and to guide climate adaptation (e.g., see Stephenson 1998; Dobrowski et al. 2011; Churchill et al. 2013;

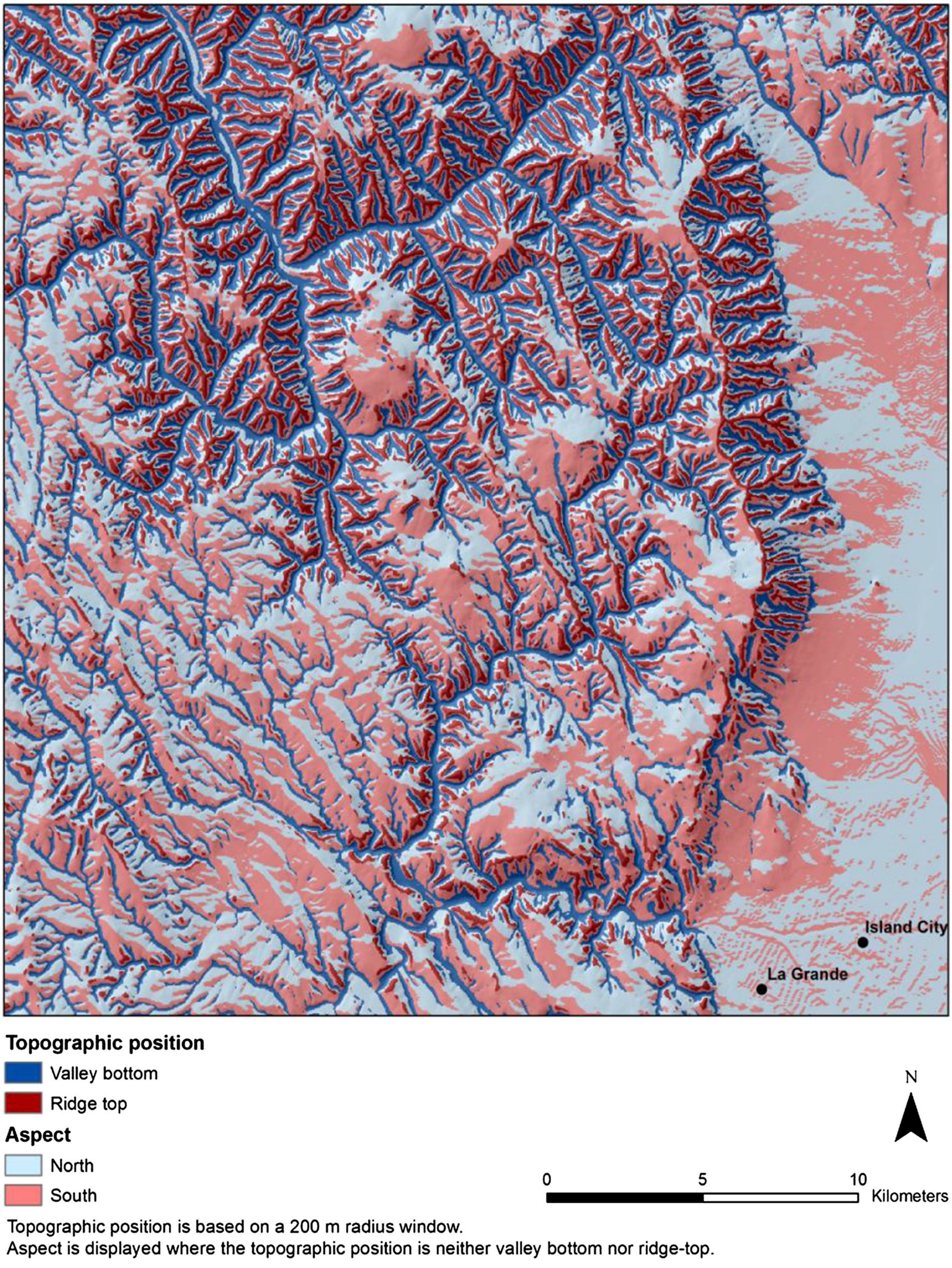
Fig. 4 Map showing north and south-facing aspect patches, and ▶ ridge and valley *bottom* topographies in the vicinity of La Grande, Oregon. Topographic position is based on a 200-m radius window. Aspect is displayed where the topographic position is neither valley bottom nor ridge top

Kane et al. 2015). Below, we provide a general approach for using topography in a landscape prescription using archetypal forest conditions as example landscapes.

Managing low- to mid-elevation south aspects and ridgelines. Southerly aspects and ridges can be managed to support fire-tolerant species in clumped tree distributions by: (1) favoring medium- (e.g., 40–60 cm dbh) to large-sized(e.g., 60–100 cm dbh, note that size ranges will depend on species and site productivity) trees; (2) promoting vegetation density and composition that is resilient to primarily low- and mixed-severity fires; and (3) maintaining relatively low vegetation density via forest thinning, prescribed burning, and/or managed wildfires. Tree size classes, tree clump and gap size distributions, and total canopy cover would vary from place to place and through time, but ranges of conditions could be calibrated from historical reconstructions (see *Principle 5,* Larson and Churchill 2012) and modified by incorporating expected climatic changes (e.g., see Churchill et al. 2013).

Managing low- to mid-elevation north aspects and valley-bottoms. North aspects and valley-bottoms generally support a mix of fire-tolerant and fire-intolerant tree species in relatively dense, often multi-layered arrangements. Because these fuel types typically support mixed surface and crown fire behavior, restorative prescriptions should allow patches of mixed and high-severity fires (see also *Principle 4*). These denser forests may also be subject to insect outbreaks. However, the naturally scattered distribution of north aspect and valley-bottom forests across the landscape (Fig. 4) typically constrains the frequency, severity, and duration of defoliator and bark beetle outbreaks by interrupting host contagion. Special attention to riparian zones is needed because such areas provide key structural elements of aquatic habitats such as large wood and undercut stream banks.

By suggesting topography as a natural template, we do not advise any strict correspondence of forest successional patches with topographic edges. Instead, applying feathered edges on the margins, for example, dry pine patches grading into dry or mesic mixed-


Island City
La Grande
Topographic position
Valley bottom
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Aspect
North
South
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Topographic position is based on a 200 m radius window.
Aspect is displayed where the topographic position is neither valley bottom nor ridge-top.

Fig. 5 Topography and physiography provided an intuitive natural template for life form, successional, and patch size patterns. This is the Mission Creek landscape just southwest of Wenatchee, in Washington State. Notice how aspect and topographic position influence wildfire and vegetation patterns: historically, south facing slopes and ridge tops display low tree density, early seral species, and open canopy vegetation conditions resulting from frequent low and mixed severity fires, where surface fire effects dominated; north facing slopes and valley bottom were denser and exhibit more moderate site climate, and less frequent but more severe wildfire disturbances. The *bottom* photo was taken in 2010, and provided courtesy of John Marshall. The *top* photo was taken in 1934, and comes from the William Osborne collection (Arnst 1985)

conifer patches(i.e., transitional zones with adjacent patches) might be more typical of the "soft edges" observed under more natural disturbance conditions (Stamps et al. 1987).

Principle 3

Disturbance and succession drive ecosystem change. Variability in climate, lifeform and successional patterns, and topographic and edaphic environments of a region (Fig. 6) determines disturbance regimes, which give rise to characteristic patterns of terrestrial and aquatic habitats (Bisson et al. 2009; Hessburg et al. 1999b; Keane et al. 2009; Merschel et al. 2014; Spies et al. 2012; Wiens et al. 2012). In the West, fire was historically the dominant disturbance; insect, pathogen, and weather disturbances were subordinate but added important variability to lifeform and successional patterns. In contrast, today's patterns are largely a by product of the cumulative effects of human action and altered disturbance regimes. Insect outbreaks and wildfires now occur at larger scales, and both are being driven by a warmer climate (Littell et al. 2009, McKenzie et al. 2004; Bentz et al. 2010; *cf.* Baker 2012; Williams and Baker 2012; Odion et al. 2014). Consequently, large and severe bark beetle outbreaks and wildfires are more rapidly driving landscape change today compared with the past. High-intensity wildfire

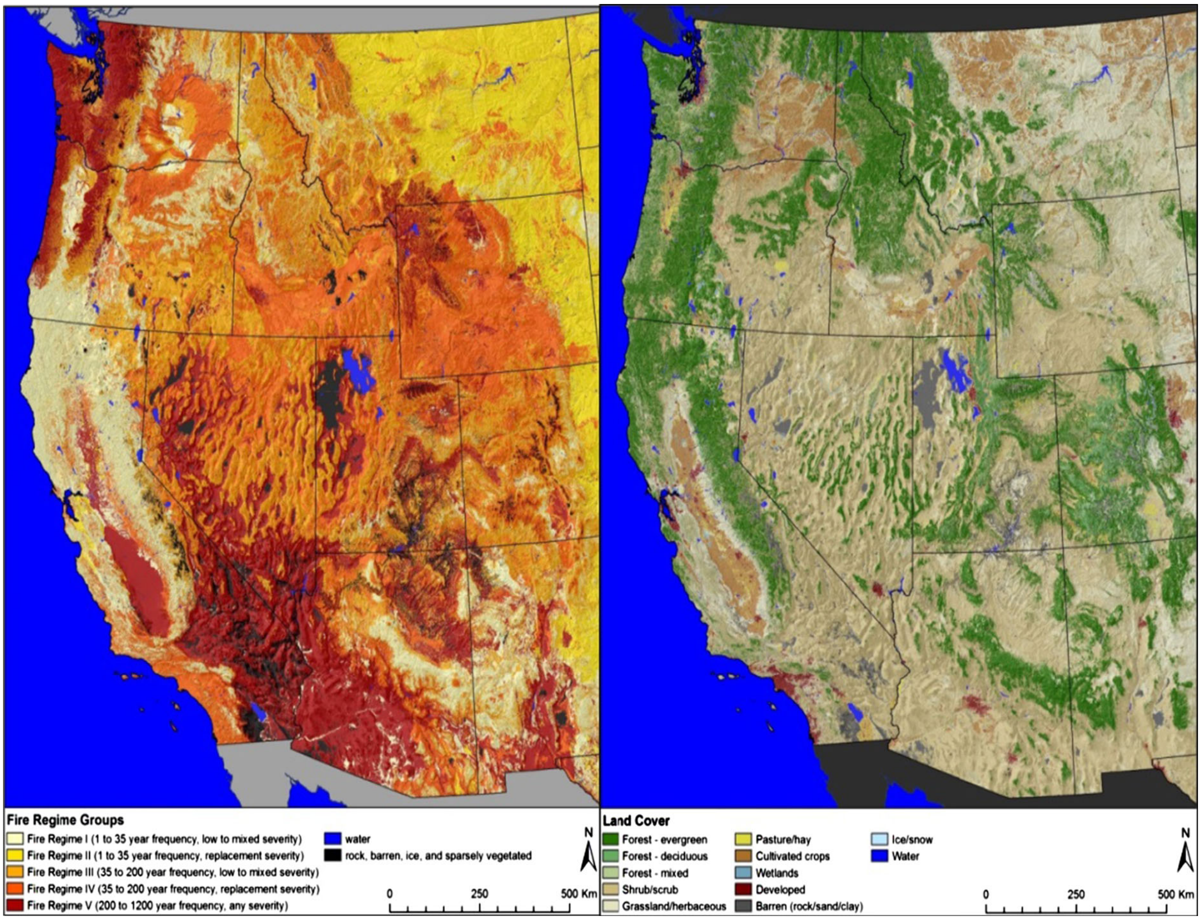


Fig. 6 Historical fire regime groups of the western United States (*left*). Note the relationship of fire regime zones to broad topographic gradients and land surface forms. Data are from www.landfire.gov. Land cover types are shown in the map to the *right*. Notice the high degree of correspondence between the fire regime and land cover maps. Both maps are shown with a 200-m resolution hill-shade with z-augmentation. Data are from the 2006 National Land Cover Dataset (http://www.mrlc.gov/nlcd2006.php)

events and insect outbreaks can rapidly change ecoregional landscape structure and impact large areas, especially in comparison to the area currently influenced by restorative treatments (e.g., see Fig. 7).

Implication

Move toward restoring natural fire regimes and the variation in successional patterns that supported them so that other processes may follow. Planning and management should identify and restore natural disturbance regimes[3] to create resilient landscapes. In some wilderness and roadless areas, the management of natural fire regimes appears to have restored successional patterns and resilient landscapes (Collins et al. 2009, Parks et al. 2015). In other places, creating landscapes where successional patterns, disturbances, and climate dynamics are more in sync will require modification of forest structure and composition patterns. This is especially true of dry to mesic mixed-coniferous forests that are currently most

[3] The fire regime includes the frequency, severity (effects), intensity (energy release), size distribution, and seasonality of

Footnote 3 continued
fires. The natural fire regime is that which generally occurs when variation in fire frequency, severity, seasonality, and extent reflects characteristic interactions between the biota, geology, and climate settings of the forest type and ecoregion (Swetnam et al. 1999; Landres et al. 1999).

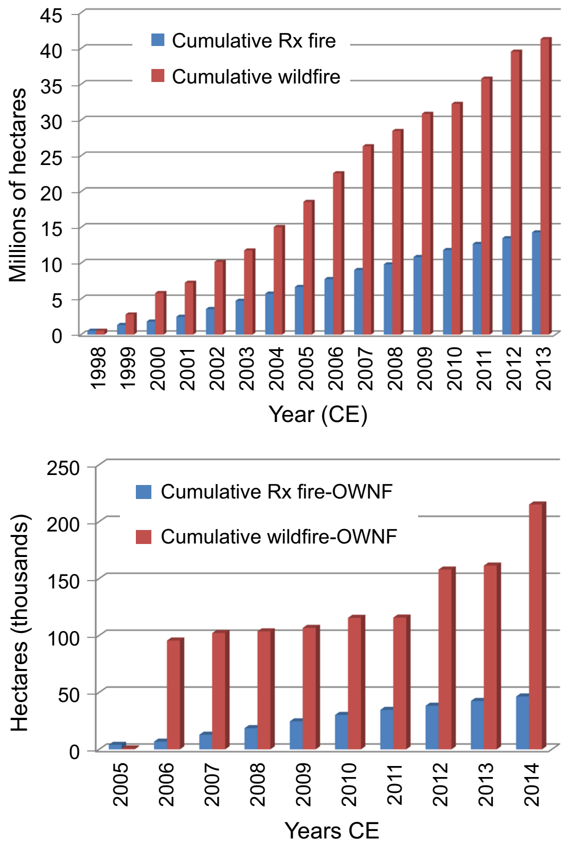


Fig. 7 (*Top*) area burned (millions of hectares) by cumulative prescribed (Rx) versus wildfires, from 1998 to 2013, on all State and federal agency lands throughout the US. Data are available at: http://www.nifc.gov/fireInfo/fireInfo_statistics.html. Note that the ratio of wild to Rx burned ha is ~3:1. (*Bottom*) area burned (thousands of hectares) by cumulative prescribed (Rx) versus wildfires, from 2005 to 2014, on the Okanogan-Wenatchee National Forest (OWNF), eastern Washington. The ratio of wild to Rx burned ha on the OWNF is ~5:1

departed from historical fire regime conditions (Agee 1998). Naturally occurring (e.g., wildfires) and well-planned human-caused disturbances (mechanical and/or prescribed burning treatments) can be used to modify successional patterns so they better match the disturbance ecology of the landscapes in question (see Box 2). Management activities should avoid the development of additional permanent roads. Rather, efforts should work within existing or reduced road networks, staying away from especially sensitive areas (Rieman et al. 2000, 2010).

The historical range of variability (HRV, Keane et al. 2009; Landres et al. 1999; McGarigal and Romme 2012; Wiens et al. 2012) of regional successional patterns can be used to inform management targets, where these reference conditions are based on climates that are similar to those anticipated in the future (Stephens et al. 2008, 2010). Moreover, the climatic variability during the HRV reference period undoubtedly overlaps with future climates, making them a useful reference. However, where HRV reference conditions are based on climates that highly differ from those anticipated in the future, they will be far less useful.

Several authors have referred to a future range of variation (FRV), which identifies alternative reference conditions that are suited to a predicted future climate (Hessburg et al. 2013; Keane et al. 2009; Moritz et al. 2011, 2013). In ecoregions where the anticipated twenty first century climate is much warmer and drier/wetter than that of the early twentieth century, FRV reference conditions will be most useful to guide restoration efforts (USFS 2012; Hessburg et al. 2013). The FRV in some ecoregions is currently being approximated using either historical or contemporary analogue landscapes with successional patterns that have experienced the predicted future climate (Hessburg et al. 2013) or via succession and disturbance simulation modeling techniques (Keane et al. 2002; Loehman et al. 2011; Miller 2007). Both techniques are useful for exploring alternative vegetation patterns that will be fostered by a changing climate and understanding desirable changes to the existing conditions.

In some cases, the restoration approach will need to recognize current vulnerabilities to uncharacteristic disturbances and landscape inertia associated with other ecological processes (Merschel et al. 2014; Stephens et al. 2008, 2010; Stine et al. 2014). For example, in eastern Oregon, Douglas-fir and grand fir regeneration has become so widespread during the period of fire exclusion that seed rain from these species makes it unlikely that ponderosa pine will re-establish as a dominant species even after fires (Merschel et al. 2014). Re-establishment of pine may necessitate extensive cover type manipulation (Stine et al. 2014).

Restoration of resilient landscapes will not be feasible everywhere and some landscape prescriptions will need to acknowledge that long-term, unavoidable shifts in landscapes toward novel or "hybrid" ecosystems have occurred (Hobbs et al. 2009). In the future, western forests will contain more people, non-native

Box 2 A greatly enlarged role for managed surface and crown fires

Conventional restoration activities take place at the stand-scale, but such activities will not likely scale up to accomplish needed ecoregional and local landscape pattern modification. Furthermore, conventional vegetation management practices alone will not restore fire regimes or mimic fire effects. Most of the work of restoring landscapes will likely need to be done using managed wildfires over large areas and prescribed burning (North et al. 2012a, 2015), with mechanical treatments in key areas that require spatial precision of outcomes and existing road access. This increased tolerance for wildfire, especially during moderate fire years and shoulder seasons, will require continued public education on the ecological role of fire, as well as changes in policies and professional incentives for forest managers. Cutting trees, whether commercially or pre-commercially, can emulate fire effects on tree density and layering, but it cannot reproduce the effects of fire on nutrient cycling, snag creation, surface fuel reduction, mineral seedbed preparation, and regenerating associated shrub and herb vegetation (Johnson 1992, Johnson and Miyanishi 1995). If not designed with clear ecological objectives and constraints, commercial timber harvest can result in removal of scarce large-sized trees to cover harvesting costs, reduced snag densities, excessive soil compaction, simplification of spatial patterns, and residual fine fuel buildup that can promote future fire spread. This is a particular concern adjacent to riverine systems, where retention of large dead wood is critical. In contrast, management ignited or managed wildfires burning under moderate fire weather conditions can often accomplish ecological objectives without timber harvest, as has been observed in some wilderness and road less areas, and in forests where mixed and high-severity fires naturally dominate (Meyer 2015).

species, an altered climate, and increased demands for carbon storage, food and water, minerals, wood and other forest products. Some long-term shifts will preclude a return to pre-development conditions (Higgs et al. 2014). Planning for sustainability will require the best efforts of resource economists and physical, biological, and social scientists.

Principle 4

Predictable patch size distributions historically emerged from linked climate-disturbance-topography-vegetation interactions. Low, mixed, and high severity[4] wildfires historically maintained heterogeneous patchworks of burned and recovering vegetation in a fairly predictable variety of successional states and patch sizes (the HRV), with insect, pathogen, and weather disturbances adding to pattern complexity (Agee 1993, 1998). Historically, landscapes were patchworks of small(10^1 to 10^2 ha) to large (10^3 to 10^4 ha) patches with dead trees, early seral grasslands and shrublands (pre-forest conditions, Swanson et al. 2010), bare ground, and patches of new forest (Fig. 8; Moritz et al. 2011; Perry et al. 2011). For example, in the Blue Mountains and Northern Cascades provinces, as much as a third of the total area that was capable of producing dry, mesic, or cold forests was in either pre-forest or early seral condition (Hessburg et al. 1999a, b, 2015). The resulting patchwork of successional and environmental conditions resisted abrupt and widespread changes at local and regional landscape scales by reducing fuel contagion and the likelihood of large and severe fires (Collins et al. 2009, Hessburg et al. 1999b; Keane et al. 2009; Malamud et al. 1998; Moritz et al. 2013; Peterson 2002; Stephens et al. 2015). Large wildfires and insect outbreaks (e.g., Miller and Keen 1960) occurred when extreme climate and weather conditions overrode the spatial controls that successional and fuel patterns, and topography provided (Littell et al. 2009; McKenzie et al. 2004; Westerling et al. 2006), but even large fires resulted in patchy successional landscapes (Cansler and McKenzie 2014).

Low, mixed, and high severity fires and resulting successional patches occurred in predictable size distributions, like those shown in Fig. 9. (Hessburg et al. 2007; Moritz et al. 2011; Perry et al. 2011). At any one time, most patches (80–95 %) were relatively small, 1's to 100's of ha, and accounted for a minority of the disturbed area (Malamud et al. 1998; Moritz et al. 2011). The remaining patches were medium- to large-sized, 1000's to 10,000's of ha, and occasionally very large, 100,000's of ha, and together these constituted the majority of area disturbed by fire (Malamud et al. 1998, 2005, Moritz et al. 2011; Perry et al. 2011). The size distribution of disturbance events and the resultant successional patch mosaic approximated a truncated power-law model (Moritz et al. 2011; Perry et al. 2011); a feature that is suspected to have held across disparate ecoregions, despite large variability in biogeoclimatic conditions. Such patterns are also found in the size distribution of

[4] Low severity fires are those where <20 % of the overstory tree cover or basal area is killed by fire and fires are generally surface fires. Mixed severity fires are those where 20–70 % of the overstory tree cover or basal area is killed by fire, and fires typically display a mix of surface and crown fire. High severity fires are those where >70 % of the overstory tree cover or basal area is killed by fire, and fires are primarily crown fires (Agee 1993).

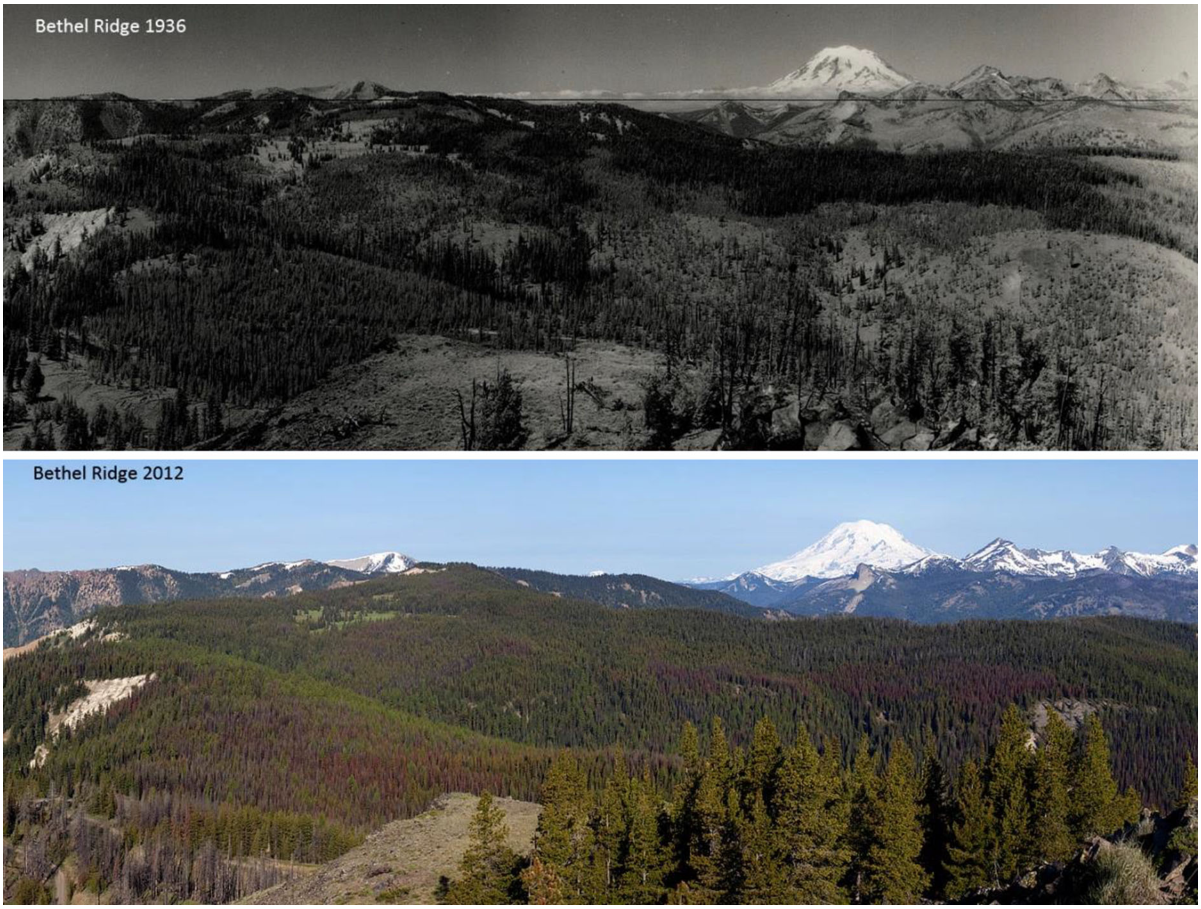


Fig. 8 Large areas of recently burned and recovering forest were commonplace in early twentieth-century forests of the inland Pacific West. This is the Bethel Ridge landscape in eastern Washington State, which is located east of Mt. Rainier and north of Rimrock Lake. Notice in the *top photograph* recently burned areas in the background that are in a pre-forest condition, while patches with seedlings, saplings, and pole sized trees are evident in mid- and foreground areas. In the *bottom photo*, it is evident that fires have been largely excluded since the *top photo* was taken, and the forest appears to be continuous with little variation in age, density or size. Notice too that many of the areas that were recently burned in the *top photo* show clear evidence of bark beetle mortality (*brown patches*) in the *bottom photo*. The *bottom photo* was taken in 2012 by John Marshall. The *top photo* was taken in 1936, and comes from the William Osborne collection (Arnst 1985)

certain topographic features (e.g., north–south aspect patches), which may indicate topographic control as a partial mechanism for ecosystem resilience to recurrent disturbances (Moritz et al. 2011; Box 3).

Implication

Move toward restoring size distributions of historical successional patches and allow changing climate and disturbance regimes to adapt them. Historical successional patch size distributions were the by product of ongoing disturbances and changes to the climate system, providing a broad landscape resilience mechanism. If successional pattern conditions today were those of pre-management era forests, we would have minimal concern for their capacity to adjust to the climatic changes we are experiencing today.

Successional patches include non-forested "openings", the largest of which may still be evident today, though their margins have been encroached upon (Arno and Gruell 1986; Coop and Givnish 2007). Smaller openings have disappeared (Skinner 1995), and their historical distribution can be determined

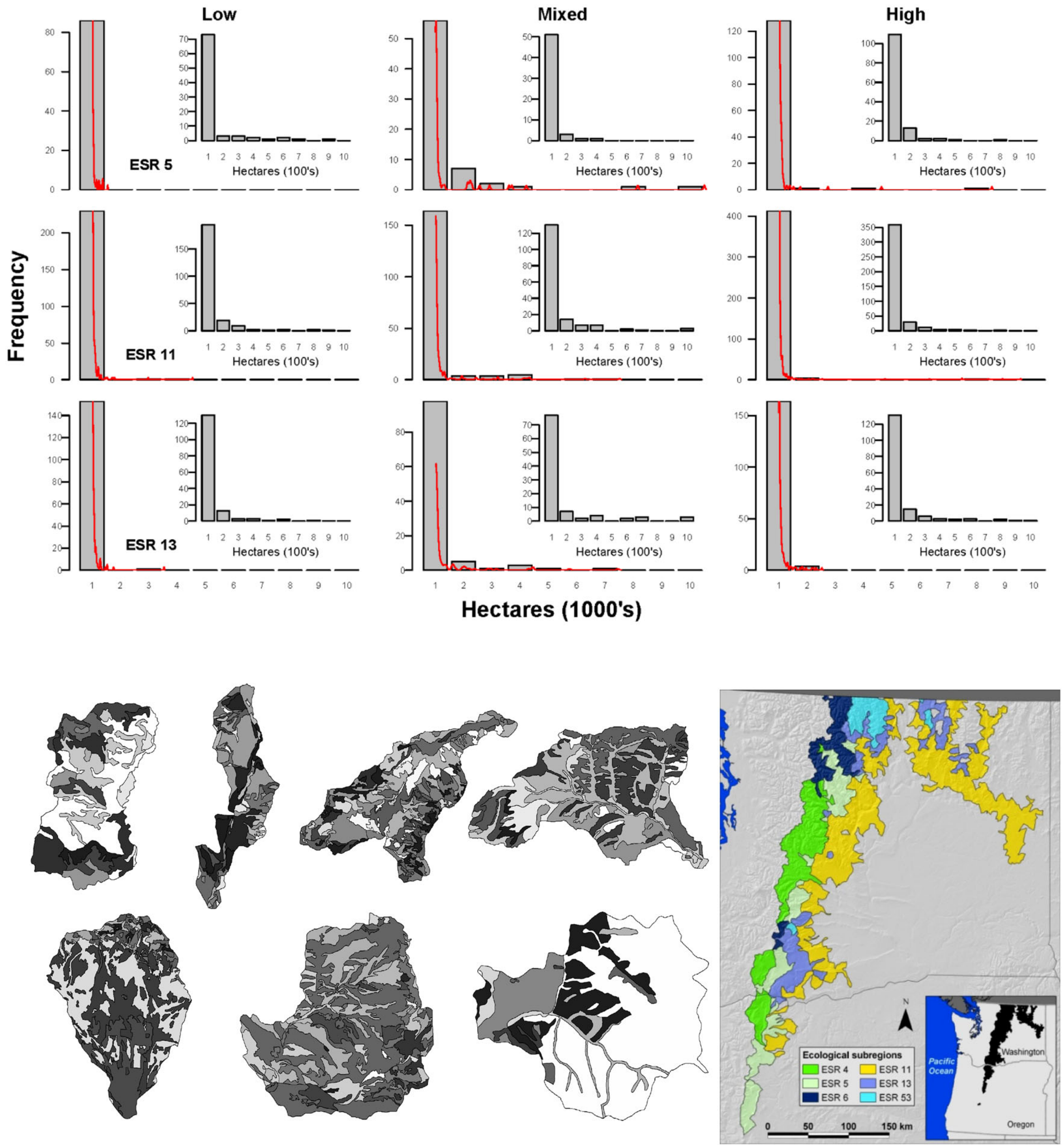


Fig. 9 Shown are maps of six ecological subregions (ESRs) in eastern Washington (*lower right*, Hessburg et al. 2000b), reconstructed historical fire severity patch size distributions within three of them (*upper*, ESRs 5, 11, and 13 (Perry et al. 2011; Hessburg et al. 2007), and example variability in historical successional patch sizes and arrangements (*lower left*, adapted from Perry et al. 2011) within ESR 13

from reconstructions of fine-scale forest structure (*Principle 5*). In the absence of local, historically derived information, landscape prescriptions should focus on increasing the frequency of variably-sized openings and successional patches (Dickinson 2014).

Patch size distributions will fluctuate as they adjust to climate, and to the proportion of the area affected by wild and managed fires and vegetation treatments (Keane et al. 2002). However, as patch size distributions of successional patches become more in sync with current climate and natural disturbance regimes, we expect that these adjustments will become less dramatic and abrupt, and offer less uncertainty to future habitat conditions.

Box 3 "Perfect storm" conditions for large wildfires

Dynamic interactions among the climate, disturbances, successional conditions and patterns of environments were the mechanism by which successional mosaics historically emerged in dry, mesic, and cold forests of the inland Pacific West. Mosaics varied across space and time, but variability was constrained by the dominant climate and disturbance influences. In contrast, today's successional patterns, fueled by a warming climate, appear to be driving more severe disturbance regimes (generally lower fire frequency and higher severity) in a kind of 'perfect storm', with uncertain ecological trajectories associated with some fires (Lydersen et al. 2014). By excluding all but the largest fires via suppression, we enable successional processes to create dense patches of stressed trees on some parts of the landscape, with higher than historical surface fuel loads, high landscape contagion, and dense canopy fuels. This successional landscape is a regional-scale condition in which wildfires are more likely to be large and often severe. Moreover, it is marked by vast areas of shade-tolerant, fire sensitive species (e.g., grand, white fir, Douglas-fir, subalpine fir, Engelmann spruce), that produce abundant seeds, and that can colonize disturbed areas, further reinforcing a broad-scale species compositional shift.

Principle 5

Successional patches are "landscapes within landscapes". Even though patches themselves define the heterogeneity of local landscapes, they too are defined by within-patch heterogeneity. Reconstructions from pre-settlement era and contemporary forests with active wildfire regimes (Fry et al. 2014; Larson and Churchill 2012; Lydersen et al. 2013; Fig. 10) show that patches in fire-prone dry and mesic mixed-conifer forests comprised fine-scale mosaics of individual trees, and tree clumps and openings (gaps) of various sizes. These spatial patterns influence patch-level resilience to disturbances, rates of succession and stand dynamics processes (Sánchez Meador et al. 2009; Stephens et al. 2008; Dodson et al. 2008; Fettig et al. 2007), and wildlife habitat characteristics (Kotliar and Wiens 1990; Dodd et al. 2006; Wiens and Milne 1989).

Implication

In dry pine, and dry to mesic mixed-conifer forests, restore characteristic tree clump and gap variation within patches. Patch level prescriptions should aim to restore variable patterns within stands and begin to dissolve the uniformity achieved in prior stand-level prescriptions (Churchill et al. 2013; Franklin et al. 2013; Reynolds et al. 2013; Jain et al. 2008; North et al. 2009); especially in even-aged stands. Pre-settlement era and contemporary forests with active wildfire regimes (e.g., Fulè et al. 2012; Harrod et al. 1999; Larson and Churchill 2012; Lydersen et al. 2013; Fig. 10) provide a reference for these conditions. In many cases, old stand and plantation boundaries can be dissolved to create large patches that better match the topographic template across a broad range of patch sizes (see *Principle 2* above) (North et al. 2009; Box 4).

Principle 6

Widely distributed large, old trees provide a critical backbone to dry pine and dry to mesic mixed-conifer forest landscapes (sensu Ellison et al. 2005; Hunter 2005). Large trees dominated the overstories of open and closed canopy, old forest patches, and they were more common across a much broader area as a remnant of former overstories after mixed and high severity disturbance (Lutz et al. 2009; Collins et al. 2011; Hagmann et al. 2013, 2014; Table 1). Whether as old forest or remnant trees, many of these large, old trees were resistant to wildfires (Fig. 11), surviving extended droughts, providing seed and genetic resources spanning centuries, and contributing important snag and cavity habitat after they died. Early seral species such as ponderosa, Jeffrey and sugar pines, Douglas-fir, and western larch were the primary old tree species in locations with more fire and drought stress. Old trees of fire intolerant species (e.g. grand and white fir, western red cedar, Engelmann spruce (*Picea engelmannii* Parry ex Engelm.), and an assortment of poplars (*Populus* spp., Marshall 1928) were more common as fire frequency decreased, and in microsites with springs, seeps, or hyporheic exchange. Patches of closed canopy, old forests were generally found in refugial settings such as north aspects, in valley-bottoms along tributary streams and creeks near a major confluence, in middle or upper headwall settings, in highly-dissected topography, and in locations that experienced less frequent wildfires by virtue

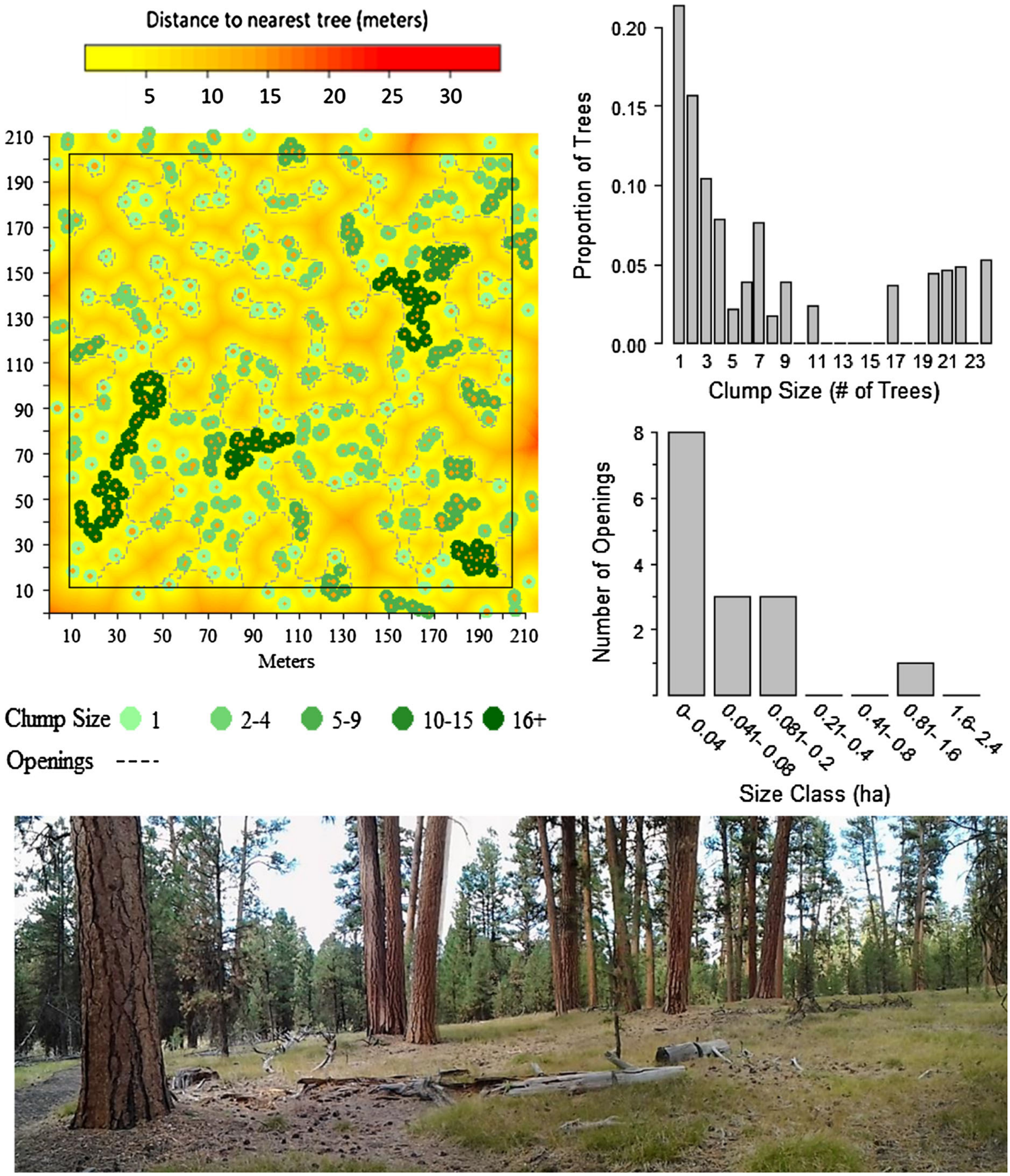


Fig. 10 Stem map (*top left panel*) and corresponding clump and opening size distributions (*right panels*) from a 4 ha plot of a reconstructed 1880 CE ponderosa pine forest on the Fremont–Winema NF, Oregon. Background color gradient shows the distance to nearest tree. A 3 m crown radius was used to project tree crowns on all trees, and a fixed distance of 6 m was used to identify clumps because most mature trees have interlocking crowns at this distance. Large openings are shown with a dashed line. Note the sinuous shape of the openings. The *bottom* photo illustrates the clumpiness of the current plot conditions

Box 4 Recommended adaptations to conventional silviculture

Recent landscape reconstructions at meso-and fine-scales (Churchill et al. 2013; Hessburg et al. 1999b; Collins et al. 2011, 2015; Larson and Churchill 2012; North et al. 2009; Lydersen and North 2012; Stephens et al. 2008; 2015; Taylor 2010) suggest that three adaptations are needed to conventional silviculture:

(1) Operational treatment units, whether mechanical or prescribed fire, should (re)create ranges and distributions of vegetation patch sizes that are characteristic of an ecoregion (Collins and Stephens 2010; Perry et al. 2011; Reynolds et al. 2013; Stine et al. 2014).

(2) Patches should be tailored to ridge, valley, and aspect topographies to achieve these patch size distributions (as above, Lydersen and North 2012; Moritz et al. 2011; Stine et al. 2014).

(3) Within patches, patterns of individual trees, tree clumps and gaps should reflect the fine-scale heterogeneity that would be expected given the natural disturbance regimes and biophysical setting (North et al. 2009; Sánchez Meador et al. 2011; Churchill et al. 2013; Kane et al. 2014; Fig. 10).

Restoring patterns across scales mimics the template that historically maintained species diversity and ecosystem functions thereby preparing the landscape for future disturbances.

Fig. 11 Widely distributed large and old trees historically provided a critical structural backbone to forest landscapes (Table 1). Historically, these old trees consisted of early seral ponderosa pine and Jeffrey pine, western larch, giant sequoia, and Douglas-fir, which displayed the thickest outer bark, but also large sugar pine, western white pine, and incense-cedar, which displayed a thinner outer bark, and were more easily scarred and killed by basal scorching. Large trees occurred in either open park-like or closed multi-story old forest patches, or they existed as a remnant of former forest conditions after a stand replacing fire with more than 70–75 % overstory mortality effects

of adjacent physical and environmental barriers to fire spread (Olson and Agee 2005; Camp et al. 1997).

Their long period of landscape service as live trees (e.g., 250–400 year), snags (30–100 year), logs (100–200 year), mulch (0–100 year), and soil carbon or charcoal (100–1000s year, Deluca and Aplet 2008) made large, old trees building blocks of the regional landscape. In addition, they are vital to many wildlife and fish habitats (Foster et al. 1998; Franklin et al. 2000; Hunter 2005; Agee and Skinner 2005; Reeves and Bisson 2009), and the legacy of large dead wood from wildfires and bark beetle outbreaks is a particularly important driver of habitat condition in the streams of many forested watersheds (Gregory et al. 2003). However, in some forests that experience frequent, low to moderate intensity fires, repeated fires can consume much of the down wood, leaving overall densities of these structural elements relatively low

Table 1 The percentage of four sampled ecoregional areas with medium- and large-sized trees in the overstory, in each of three crown cover classes

Ecoregion	Percentage area with medium-[a] and large-sized[b] trees by crown cover (CC) class							
	10–30 % CC[c]		40–60 % CC		>60 % CC		Total % area	
	H[4]	C	H	C	H	C	H	C
Blue mountains	*23.3*	**18.4**	*11.9*	**6.7**	*4.5*	**2.1**	*39.6*	**27.2**
Northern glaciated Mountains	*11.2*	11.2	*7.1*	6.7	*3.8*	6.3	*22.0*	24.2
Northern cascades	*18.2*	18.2	*15.0*	**12.7**	*8.8*	**6.9**	*41.9*	**37.9**
Southern cascades	*23.3*	17.9	*15.1*	18.9	*2.0*	7.5	*40.3*	44.3

Values in bold typeface indicate a significant reduction. Data are from the Interior Columbia Basin project (Hessburg et al. 1999a). Early twentieth-century conditions are highlighted in *gray*

[a] Medium trees = 40.5–63.5 cm DBH

[b] Large trees ≥ 63.5 cm DBH

[c] CC = denotes actual crown cover class, where maximum CC = 100 %. Crown cover was photo-interpreted in 10 % increments, and class percentages were expressed as class midpoints; e.g., 10 % = 5 to 14 % CC, 20 % = 15 to 24 % CC (Hessburg et al. 1999b). Crown cover classes above are regroupings of the decile classes

[d] H, C = historical, current conditions, respectively

and patchily distributed. For example, this was observed in northwestern Mexico, where spatial variability in dead wood resources was measured in Jeffrey pine-mixed-conifer forests with relatively intact fire regimes (Stephens 2004; Stephens et al. 2007).

Table 1 shows the historical percentage area of four fire-prone provinces in eastern Oregon and Washington with remnant medium- and large-sized old trees. These data show that remnant medium- and large-sized old trees occupied partial overstories of up to 40 % of patches, regardless of their successional condition. Early twentieth century timber inventories show that 68 % of the Warm Springs and Klamath Indian reservations in central Oregon had at least 12 trees per hectare over 53 cm diameter at breast height (Hagmann et al. 2013, 2014). Their widespread presence suggested that remnant old trees were prevalent and important features of fire-prone landscapes.

Implication

Retain and expand on existing relict trees, old forests, and post-disturbance large snags and down logs in these types. In many dry pine and mixed-conifer landscapes, restoring the pattern and abundance of old trees and old forests should be a central theme of both regional and local landscape planning (Franklin and Johnson 2012; Franklin et al. 2013; USFS 2012; Spies et al. 2006). In other locations, recent bark beetle outbreaks and wildfires have created an abundance of snags; the largest among these are especially useful to retain as snag and down wood structure. Most current USFS Standards and Guidelines in Forest-level planning call for average snag and down wood conditions replicated over thousands of ha. Observations of patchily distribution snags and downed wood associated with frequent fire regimes argue against uniform prescriptions in dry forest landscapes (Holden et al. 2007; North et al. 2009). Local landscape restoration projects should increase abundance of closed canopy, old forest patches, especially in refugial settings (e.g. Franklin et al. 2013). To improve their longevity, restoration projects can be used to help provide fire-tolerant contexts surrounding them, (Box 5).

Principle 7

Land ownership, allocation, management and access patterns disrupt landscape and ecosystem patterns. Land ownership and allocation boundaries within ownerships are a byproduct of historical social and political decisions that were indifferent to the underlying ecology. The sum of these decisions and subsequent management differences produced a landscape fragmented by ownership and allocation (Fig. 12). Disparate and contradictory goals across land allocations and ownerships create untenable management situations (Rieman et al. 2015). For

Box 5 Protect remaining live old trees and retain large old trees and snags after fires

Restorative management activities in many dry pine and mixed conifer landscapes should maintain existing patches of old forests, and retain remnant medium- and large-sized early seral trees where they occur. To improve the longevity of larger early seral trees, restorative activities would include thinning and removing neighboring shade-tolerant trees to reduce competition for water and nutrients, and removing nearby surface and ladder fuels to reduce fire intensities that would threaten their long-term survival. Furthermore, many south-facing aspects and ridgetops no longer support a characteristic abundance of early seral trees of any size and age. These settings should be evaluated for their ability to support the long term survival of early seral trees as the climate warms and dries. If deemed suitable, such sites could be emphasized for re-establishing thriving new populations, which in turn can be maintained through natural or prescribed fires and/or mechanical fuels reduction. Many existing ponderosa pine plantations can be managed and tended for future old pines as well. Where post-fire fuels are a bonafide reburn concern, salvage treatments should focus on removal of small trees and emphasize retention of large-trees, both living and dead.

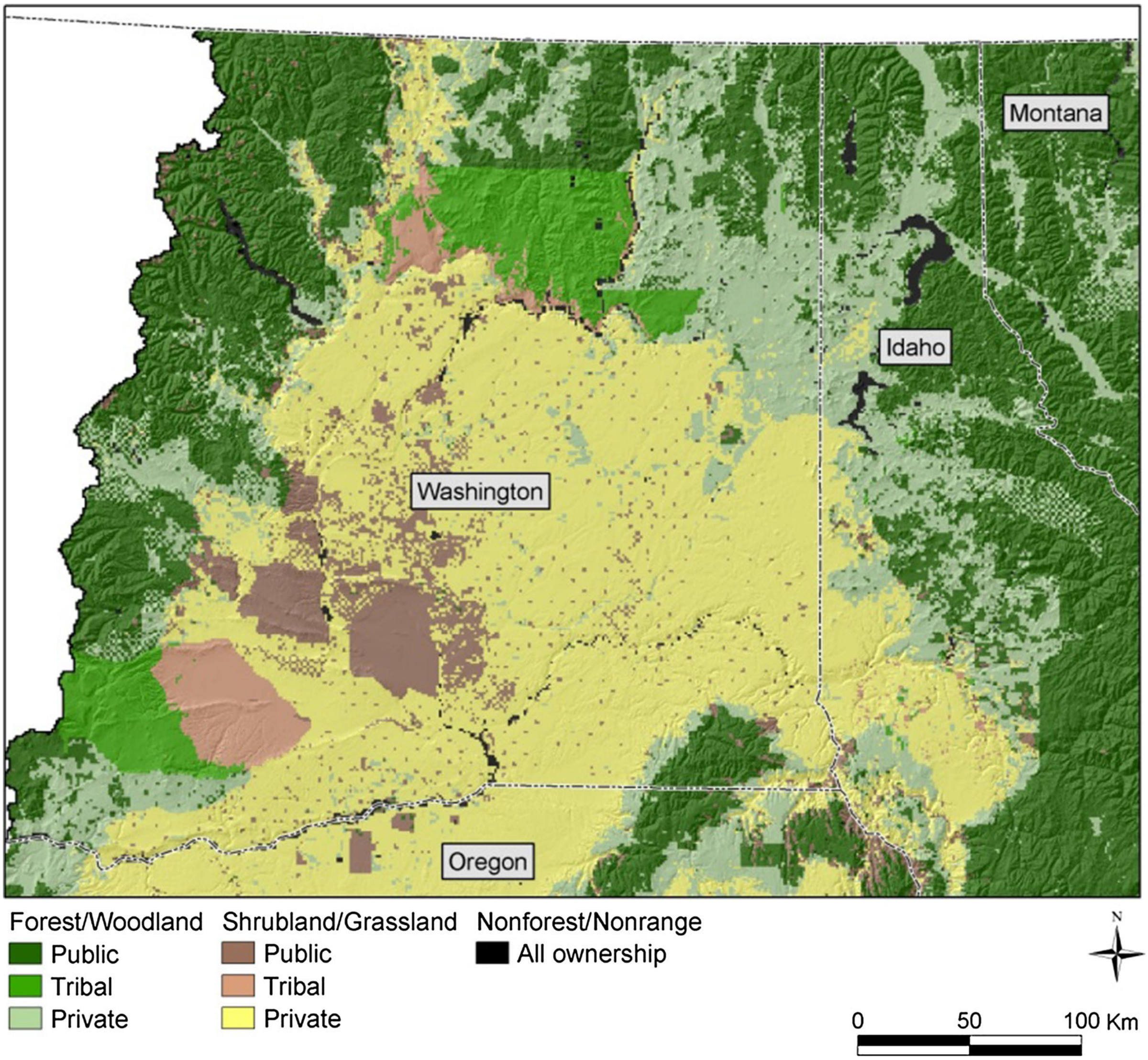


Fig. 12 Fragmentation of eastern Washington forests, grasslands, and shrublands by land ownership. Note that forests are shown in *green* and shrublands and grasslands are shown *brown* and *yellow*. Habitat fragmentation arises among mixed ownerships via varied management goals and histories, and resulting land and resource conditions

Box 6 Decrease impacts of legacy roads

Landscape restoration requires addressing the ongoing impacts of existing road networks on forest ecosystem processes and functions. The effect of road networks on aquatic and terrestrial ecosystems is well established (Bisson et al. 2003; Forman 2003; Gaines et al. 2003;Reed et al. 1996; Luce and Black 1999; Trombulak and Frissell 2000; Raphael et al. 2001). Past management has left extensive and expensive legacy road networks, which are now declining in condition. These roads deliver chronic sediment to nearby rivers and streams, and disrupt flow regimes. Deferred maintenance on retained roads yields persistent adverse impacts to fish and wildlife habitats. In addition, road systems function as alternative drainage networks, which significantly disrupt the timing and magnitude of flows and subsurface hydrology. However, not all roads are equally damaging or influential. Instead, most of the chronic sediment, channel confinement, barrier, and flow issues are associated with a fraction of the existing network, and these roads are readily identifiable. Landscape restoration projects should prioritize elimination, upgrading, or movement of these most damaging roads. Roads located in valley-bottom settings that restrict normal floodplain functioning are among those most damaging to aquatic habitat. Removal of these roads and floodplain restoration is especially important to recovering native aquatic species, and will require planning and coordination across ownerships and interest groups.

example, fire management objectives often differ on either side of a wilderness boundary (Knight and Landres 1998). Likewise, land use zoning has resulted in a confusing set of regulations that apply inconsistent environmental protections across different ownership types. As a consequence, today's disturbance and climate change vulnerabilities, terrestrial and aquatic species habitat connectivity, and road system issues cannot be resolved by any landowner working in isolation (Box 6).

Implication

Work collaboratively to develop restoration projects that effectively work across ownerships, allocations, and access needs. Landscape prescriptions must be implemented at a relatively broad scale to be ecologically effective, particularly in the context of restoring disturbance regimes. To be socio-politically effective, restoration plans need cross-boundary collaboration and problem solving (Tabor et al. 2014; Wondolleck and Yaffee 2000). Collaboration on a project from conception through design, implementation, and monitoring can expand options for management in the long run, and create synergies that are otherwise unavailable. Moreover, litigation history shows that restoration planning greatly benefits from involving all stakeholder groups who have a vested interest in the outcomes (Culhane 2013). Partner interactions create the opportunity to daylight concerns before they become litigious, and create landscape-level prescriptions that can accommodate them by design (Larson et al. 2013).

Forest collaboratives are well suited to cross-ownership and multi-stakeholder planning (Cheng and Sturtevant 2012; Charnley et al. 2014), and there are significant opportunities to coordinate activities that exceed the capacities of individual landowners. For example, in the state of Washington, USA, the northern spotted owl is federally listed as an endangered species. Federal land managers and the Washington Department of Fish and Wildlife manage most of the current nesting, roosting, and foraging habitats, while dispersal habitats often occur on intermingled Washington State Department of Natural Resources trust lands (USFWS 2012), which are managed as working forests. Road maintenance, removal, and closures, and restoration of fish and wildlife habitats and connectivity all require a similar high degree of coordination.

Implications emerging from all seven principles

Emerging from all seven principles is the idea that *landscape prescriptions* are foundational to restoration. Landscape prescriptions are a way for managers to implement the principles outlined above and to move beyond stand-centered forest management.

A landscape prescription provides guidance for landscape composition, structure, and spatial arrangement in terms of the elements comprising the next lower level of the hierarchy. We identified four hierarchical levels in *Principle 1*; hence landscape prescriptions are needed at three levels:

- *Large-scale ecoregional prescriptions* are important to reconnecting broad habitat networks and rescaling disturbance processes.
- *Local landscape prescriptions* define objectives for successional patch types, size distributions, and

spatial arrangements across the topographic template.
- *Patch-level prescriptions* describe target conditions within successional patches.

Linked evaluations and prescriptions are needed at each level where landscape change has been significant and restoration is warranted.

Ecoregional prescriptions are strategic—they highlight priority areas for reconnecting habitats and conditions under which wildfires may/may not contribute to restoring desirable local landscape patterns (North et al. 2012a). Ecoregional prescriptions should identify areas where post-disturbance silviculture or burning may be appropriate/inappropriate, and where wildfires can contribute to restoration (Allen et al. 2002; Reinhardt et al. 2008; Peterson et al. 2015). Ecoregional prescriptions should provide clear guidance for reestablishing large-scale ecoregional connectivity for wide-ranging and migratory aquatic and terrestrial species.

Local landscape prescriptions are tactical—they identify specific project areas where treatments can begin to restore ecoregional patterns and processes for multiple resources (Box 7). Local landscape

Box 7 A local landscape prescription on the Colville National Forest

We provide here an example landscape prescription from a 9500 ha mixed-conifer watershed in northeast Washington that historically supported a predominantly mixed-severity fire regime, but has been modified by fire suppression, grazing, and logging. The landscape prescription was derived from an equally-weighted HRV and FRV departure analysis that was specific to the watershed (see Hessburg et al. 2013). The basis for the prescription is thus, one part departure from HRV pattern conditions, and one part climate change adaptation, in a bet-hedging strategy to conserve maximal future options. The landscape prescription provides clear, spatially-mapped recommendations to managers on where to modify forest structure, composition, and the overall distribution of patch sizes. The prescription intentionally avoids statements about average stand conditions to facilitate creation of heterogeneity at multiple spatial scales. Improved alignment of cover type and structure conditions with topography and biophysical settings, and more naturally occurring disturbance regimes (Fig. 13), were additional goals. Treatment type for different portions of the watershed (e.g. no-treatment, mechanical, prescribed or wildfire) was also identified based on treatment need, road access, and other factors. For example, the prescription for roadless areas of the watershed was to leave them alone to grow into large tree, closed canopy forest in cool, moist refugial topographic locations, and to allow managed wildfire to create stand initiation and open canopy patches in drier areas, where feasible. An abridged version of the prescription follows:

Objectives for the whole watershed:

- Reduce landscape fragmentation by increasing patch size of most cover-structure types, as well as connectivity in some cases.
- For all forested cover types, consolidate and expand approximately ½ of the small patches (1–50 ha) into 100-400 ha patches, where possible.

In the dry forest area of the watershed:

- Increase the area of the ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) cover type with large and old over story trees, from 3 to 12–15 % of the watershed area.
- Increase the area of woodland cover types from less than 1 to 2–3 % of the watershed area. Increase the range of patch sizes to 40–125 ha, where possible.
- Reduce the amount of the Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) cover type from 25 to 8–12 % of the watershed area, especially in young forest multistory and stem exclusion structures.

In the mesic and cold forest area of the watershed:

- Increase the area of the ponderosa pine cover type from 2 to 8–10 % of the watershed area. Promote old forest structure as well as stand initiation using wild and prescribed fires to fullest advantage.
- Increase the area of the Douglas-fir cover type from 8 to 20–30 % of the watershed area. Promote open and close canopy old forest and reduce stem exclusion structure.
- Increase the patch size range of lodgepole pine (*Pinus contorta* Dougl. ex. Loud.) and western larch (*Larix occidentalis* Nutt.). Increase area in stand initiation.
- Increase the area of hardwood, shrub, herb, and woodland cover types from less than 1 % of the area to 4–7 % of the watershed area. Increase the range of patch sizes to 10–25 ha.
- Reduce the area of the subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.) cover type from 12 to 3–4 % of the watershed area, and that of the western redcedar (*Thuja plicata* Donn ex D. Don) cover type from 6 to 2–3 % of the watershed area.

Outside areas of old multi-story forest in dry, mesic, and cold forest, reduce the total area with high fuel loads (surface, ladder, and crown fuels) and increase the total area and size of patches with low fuel loads, especially on south-facing aspects and on ridgetops.

prescriptions provide guidance about how to arrange different successional patches across the topographic template (*Principle 2*), the target patch size distributions (*Principle 4*), and how to protect and increase abundance of legacy old trees (*Principle 6*). Articulating how silvicultural treatments, prescribed fire, and wildfire can work together to restore disturbance regimes (*Principle 3*) will be necessary for a successful local landscape prescription. Terrestrial and aquatic habitat and road system restoration opportunities should be linked in local landscape prescriptions to take advantage of simultaneous problem-solving opportunities (Rieman et al. 2010). For example, local prescriptions can identify harmful road segments and fish passage barriers, opportunities to expand local fish strongholds and rebuild larger, more productive fish and wildlife habitat patches (sensu Rieman et al. 2000, 2010).

Patch-level silvicultural prescriptions provide targets for the structure, density, composition, and pattern of a patch, or group of patches, that are tailored to the current vegetation conditions and biophysical setting of the site (*Principle 5*). Targets for heterogeneity within patches can be expressed in terms of the numbers and sizes of widely-spaced individual trees, tree clumps, and openings (Churchill et al. 2013), or using other metrics and tools (e.g. Jain et al. 2008; Reynolds et al. 2013). Treatment units, which flow from patch-level prescriptions, are the portions of a local landscape that will be treated to achieve the desired targets. They can comprise a single patch, part of a patch, multiple patches, or even cut across patch boundaries. Critically, treatment units should not define landscape pattern as they currently do in many landscapes.

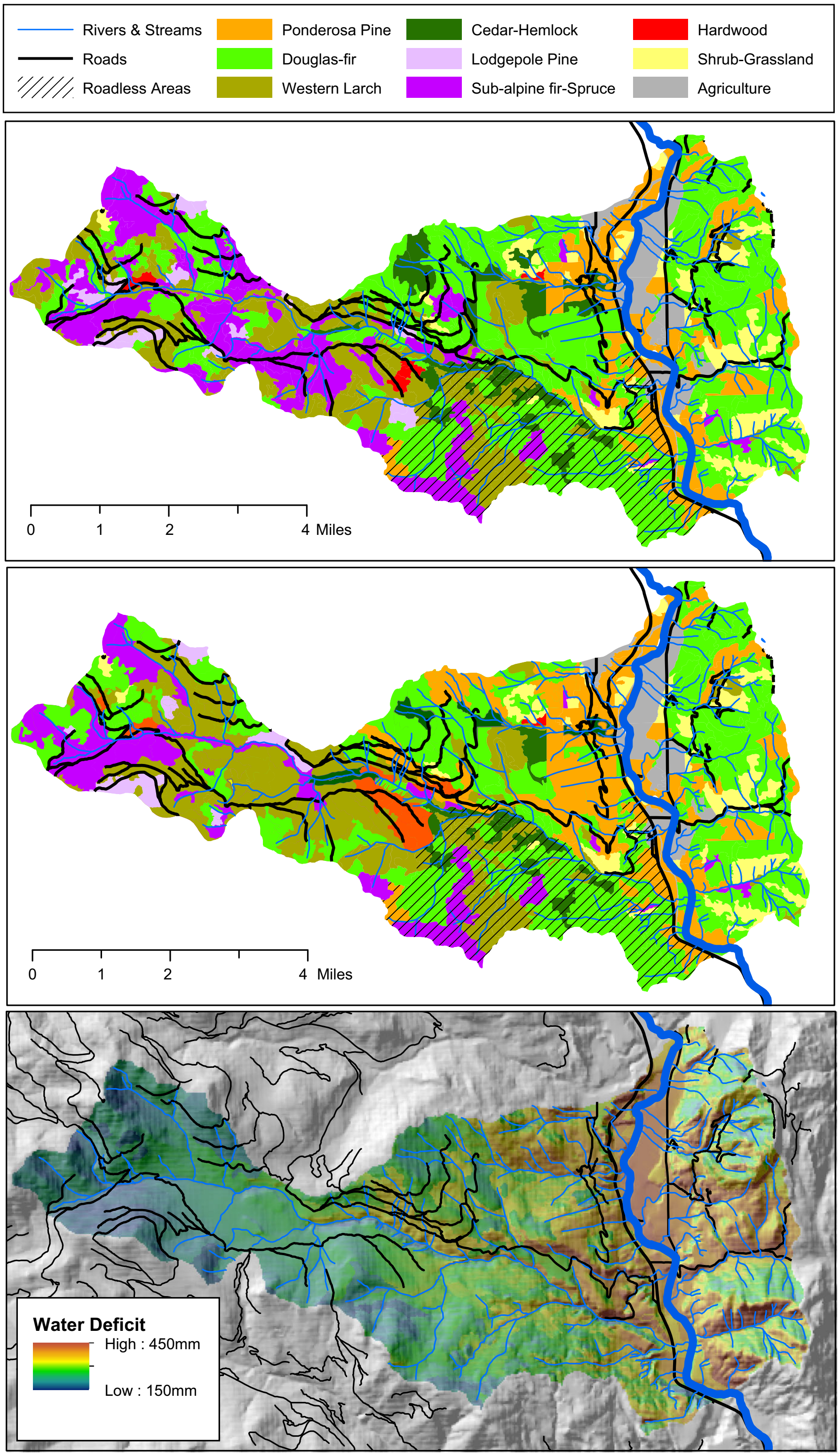
Summary

Managing fire-prone landscapes today to increase their climate- and fire-resilience poses immense challenges to managers, in planning and execution (North et al. 2012a, b). The current management environment is internally and externally polarized by mistrust, and a concern that land managers may never make a paradigm shift to sustainable ecosystem management (sensu Grumbine 1994; Spies et al. 2012, 2014; Dunlap and Mertig 2014). Here we argue that the time for that shift has come, and many partners of federal lands wish to help it along (Brown et al. 2004; Cheng and Sturtevant 2012; Charnley et al. 2014).

We provide core principles gleaned from recent research to advance management planning and treatment design to better incorporate natural processes, climate change, and operational limitations into management. We emphasize pine and mixed-conifer forests of the interior Pacific, but the principles and implications we outline are applicable elsewhere, especially to the dry pine and mixed-conifer forests of the southwestern US and Rocky Mountain regions. Central to our proposed framework are the notions that:

- Prior to the modern management era, western forest and rangeland landscapes were spatially heterogeneous at several scales.
- This heterogeneity resulted from native ecological and physical processes and their interactions with forest habitat and successional patterns.
- These processes created habitat and networking conditions to which native flora and fauna are adapted.
- Forest and rangeland conditions and their associated species were adaptable and resilient to shifts in climate and recurrent contagious disturbances.
- Multi-scale heterogeneity has been altered in many areas over the course of management.
- Disturbance processes, particularly wildfires and bark beetle outbreaks, will continue to be primary determinants of patterns in managed and unmanaged landscapes.
- Future climatic changes may surpass those experienced in the Inland Pacific region during the last interglacial. In that event, historical insights can inform our understanding of ecosystem responses to climate forcing, but management adaptations will need to be forward-looking.
- Collaboration on restorative management among managers, stakeholders, and scientific disciplines is essential because forest landscapes are coupled terrestrial and aquatic, social and ecological systems, and people have a stake in the outcomes. Collaboration and negotiation are imperative precursors to management.

Our principles stress the importance of scale and the interconnectedness of landscapes across scales. The traditional view of managing stands of trees in isolation is a relic of the past.


Rivers & Streams
Roads
Roadless Areas
Ponderosa Pine
Douglas-fir
Western Larch
Cedar-Hemlock
Lodgepole Pine
Sub-alpine fir-Spruce
Hardwood
Shrub-Grassland
Agriculture
0 1 2 4 Miles
0 1 2 4 Miles
Water Deficit
High : 450mm
Low : 150mm

◀**Fig. 13** Cover types and soil moisture deficit for the Orient subwatershed on the Colville National Forest in North-Central Washington (9500 ha). *Top panel* shows current cover types and *middle panel* shows projected cover types after potential treatments guided by a landscape prescription. Cover types are named after the dominant species, but contain multiple species. Potential treatments are not proposed treatments. Proposed treatments will be released for public comment and evaluated during a formal NEPA planning process. Potential treatments included mechanical thinning and prescribed fire. The major goals of the landscape prescription were to increase patch sizes and shift cover and structure types to species better aligned with the topography and biophysical conditions as illustrated on the *bottom panel*—only changes in cover types are shown here. Climatic water deficit on the *bottom panel* was calculated using modified Thornthwaite methods described in Churchill et al. (2013)

Landscape restoration will require the integrated use of vegetation treatments, prescribed and managed fires to achieve the necessary changes in landscape patterns, at scales broad enough to be meaningful. Management can be informed by natural landscape patterns that result from interactions between biotic communities, disturbances, and physiographic environments (DeLong and Tanner 1996). Such conditions can be quantified using past vegetation patterns HRV, and where appropriate, climate change analogue conditions, and used to help craft landscape prescriptions (Box 7) that provide guidance on the amount, distribution, and pattern of successional conditions to create through management actions.

Wildfires and insect outbreaks are an inevitable part of future landscapes. Future management should aim to restore more resilient vegetation patterns that can help to realign the severity and patch sizes of these disturbances, promote natural post-disturbance recovery, reduce the need for expensive active management, and drastically reduce the role and need of fire suppression.

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