Landscape Ecol (2007) 22:5–24
DOI 10.1007/s10980-007-9098-2

RESEARCH ARTICLE

Re-examining fire severity relations in pre-management era mixed conifer forests: inferences from landscape patterns of forest structure

Paul F. Hessburg · R. Brion Salter · Kevin M. James

Received: 16 August 2006 / Accepted: 23 March 2007 / Published online: 17 April 2007

Abstract For some time, ecologists have known that spatial patterns of forest structure reflected disturbance and recovery history, disturbance severity and underlying influences of environmental gradients. In spite of this awareness, historical forest structure has been little used to expand knowledge of historical fire severity. Here, we used forest structure to predict pre-management era fire severity across three biogeoclimatic zones in eastern Washington State, USA, that contained extensive mixed conifer forests. We randomly selected 10% of the subwatersheds in each zone, delineated patch boundaries, and photo-interpreted the vegetation attributes of every patch in each subwatershed using the oldest available stereo-aerial photography. We statistically reconstructed the vegetation of any patch showing evidence of early selective harvesting, and then classified them as to their most recent fire severity. Classification used published percent canopy mortality definitions and a dichotomized procedure that considered the overstory and understory canopy cover and size class attributes of a patch, and the fire tolerance of its cover type. Mixed severity fires were most prevalent, regardless of forest type. The structure of mixed conifer patches, in particular, was formed by a mix of disturbance severities. In moist mixed conifer, stand replacement effects were more widespread in patches than surface fire effects, while in dry mixed conifer, surface fire effects were more widespread by nearly 2:1. However, evidence for low severity fires as the primary influence, or of abundant old park-like patches, was lacking in both the dry and moist mixed conifer forests. The relatively low abundance of old, park-like or similar forest patches, high abundance of young and intermediate-aged patches, and widespread evidence of partial stand and stand-replacing fire suggested that variable fire severity and non-equilibrium patch dynamics were primarily at work.

Keywords Fire severity · Mixed conifer forests · Dry forests · Non-equilibrium dynamics · Mixed severity fire · Ecoregions · Inland Northwest USA · Historical range of variability

Introduction

The concept of fire severity, the effects of a wildfire and its mosaic of intensities on the vitality of biota, is useful to land managers. For example, public land managers are required to maintain viable populations (*sensu* Hunter 1990) of listed or sensitive native species (Endangered Species Act of 1973). To accomplish this task, they will imitate the pattern and effects of historical fires when they distribute management intensities across a landscape (e.g., see Hunter 1993; Hunter et al. 1988). This is an intuitive

---

P. F. Hessburg (✉) · R. B. Salter · K. M. James
Pacific Northwest Research Station, USDA Forest Service, Wenatchee, WA 98801-1229, USA
e-mail: phessburg@fs.fed.us

approach because the ebb and flow of disturbances and resultant patterns of forest structure supported a rich flora and fauna and the native disturbance regimes. Indeed, recent emphasis on fire history studies and the historical range of variability is driven by coarse-filter native species conservation ideas (Agee 2003; Hunter et al. 1988; Landres et al. 1999; Thompson and Harestad 2004). Despite knowledge of linkages between patterns of fire severity and landscape conditions, there has been little use of forest structural conditions to characterize patterns of historical fire severity. That is the topic of this paper.

The fire history literature from the Inland Northwest United States couples dry mixed conifer forests (hereafter, dry forests) of the pre-management era (ca. 1900) with high frequency (once every 1–25 years), low severity fire regimes (Agee 1993, 1994, 1998; DeBano et al. 1998; Everett et al. 1997, 2000; Heyerdahl et al. 2001; Weaver 1943, 1959, 1961; Wright and Agee 2004). Prior to management, dry forest patches and their structural features were thought to be in a relatively stable equilibrium with their environment, the regional climate, and primary disturbance processes. Old, multi-cohort, park-like ponderosa pine (*Pinus ponderosa*) stands (referring to actual vegetation) were thought to be the most stable structures, and they were maintained by high frequency, low intensity surface fires, whose positive feedback ensured continued low severity fire and persistence of the park-like conditions. In the equilibrium model, new cohorts were recruited to the understory after each disturbance, and the grain of disturbance and recruitment was relatively fine (10^{-3}–10^{0} ha), amounting to textural change in the pre-disturbance structure and arrangement of cohorts within a patch. Subsequent surface fires (those lacking significant tree torching or crowning fire) destroyed much of the recruited understory. The overstory was multi-cohort, uneven-aged, and few understory trees were recruited to the overstory in a given decade. In time, the overstory acquired an even-aged, single cohort appearance because older cohorts had slowed in growth and younger cohorts increased in size. Stand replacement was thought to be uncommon; relatively slow attrition and recruitment accounted for the persistence of an overstory.

In contrast, historical moist mixed conifer forest (hereafter, moist forest) patches were associated with low, mixed, and high severity fires, and mixed severity fires were thought to be most influential (Agee 1990, 1993, 1994, 1998, 2003; Wright and Agee 2004). The conceptual model of moist forest patches was one of non-equilibrium dynamics, variable fire severity, and transient structures. In the non-equilibrium model, new cohorts were recruited after each disturbance; the grain of disturbance and recruitment could be highly variable, ranging from fine to relatively coarse within patches (10^{-3}–10^{2} ha), and representing minor to major changes in the pre-disturbance structure, composition, and arrangement of cohorts. Subsequent fires may be low, mixed, or high severity destroying little to nearly the entire understory that is recruited, and perhaps any associated overstory. The overstory may be multi-cohort or single cohort, and even-aged or uneven-aged, and understory trees may be slowly recruited to the overstory, or the understory may become the overstory.

Since the middle of the 20th century, historical dry forest patches were thought to conform to the stable equilibrium model (Weaver 1943, 1959, 1961). Here, we will not suggest that Weaver misinterpreted fire frequency or severity; rather, we suggest that other fire frequency and severity storylines were also probable, and that ordinary spatio-temporal variation in fire regime and structural features of dry forests may be larger than could be sampled at one or even several locations.

Potential bias in point sampling of fire survivors

One reason that low severity fires have been coupled with dry forests is that estimates of historical fire severity have been based on point sampling of recorder trees. In fire history studies, recall that recorder trees directly record high (kills the tree) or low severity (scars the tree) fires; mixed severity is inferred from mortality expressed across the sample in a given fire year. Recorder trees, snags, or logs exist because at the point where they are positioned, fires were generally low impact. The inference has been that if the impact on the recorder was low, the severity in the surrounding area must also have been low. This type of inference would tend to favor finding low severity fires and underestimating likelihood of fires of other severities (e.g., see Baker and Ehle 2001; Swetnam and Baisan 1996).

Defining mixed conifer forests

Much of the extant western US fire history literature associates a dominant fire regime with the potential vegetation type, not the actual vegetation cover type, because site climate and the fire tolerance of the vegetation cover are thought to primarily influence regime (e.g., see Agee 1998; Arno et al. 1985; Hann et al. 1997). We evaluate this assertion using the potential vegetation type to group mixed conifer environments that support similar successional pathways, and absent disturbance, the same shade tolerant species (Keane et al. 2002; Steele and Geier-Hayes 1989). Mixed conifer forests of the eastern Washington Cascades are typically divided into two broad potential vegetation types, dry and moist mixed conifer, due to obvious differences in site climate and tree productivity, and we do the same here. Whether dry or moist forest, the actual vegetation types occurring in either type are roughly the same: Primary cover types are ponderosa pine, Douglas-fir (*Pseudotsuga menziesii*), and grand fir (*Abies grandis*), or combinations of these. Additional secondary cover types include western larch (*Larix occidentalis*), lodgepole pine (*Pinus contorta*), aspen, and cottonwood (*Populus* spp.). For cross-reference, we represent dry forests as the driest Douglas-fir and grand fir plant associations (Lillybridge et al. 1995). We exclude ponderosa pine potential vegetation types from dry forest because they are ecotonal woodland types, and we suspected they represented unique fire ecology. We represent moist forests, as types on the moist end of the Douglas-fir and grand fir series.

Forest structure holds untapped clues

Our methods were based on the premise that the pattern and abundance of successional or structural stages of pre-management era landscapes held important clues to the historical distribution of fire severity. We knew that spatial patterns of forest structure reflected the broad context of biophysical gradients, human influence, and ecosystem processes, but we suspected that patterns would primarily reflect disturbance and recovery history (*sensu* O'Hara et al. 1996; Spies 1998).

Many have documented effects of fire exclusion and domestic livestock grazing early in the 20th century (e.g., Belsky and Blumenthal 1997; Hessburg and Agee 2003; Hessburg et al. 2000c, 2005; Langston 1995; Robbins 1999), and these are potentially confounding factors to reconstructing severity from forest structure. However, considering them did not help to explain the wide distribution early in the 20th century of stand initiation (1–40 year old) and young to intermediate-aged (50–150 year old) forest structures in the dry forests (this dataset). For example, in eastern Washington, our earliest stereo aerial photography (1930–1940s) of dry forests showed that 71% of the area, had understories dominated by pole-sized and larger trees (12.7–63.5 cm d.b.h.). Fire exclusion and grazing could not explain understory trees this large, and over such a vast area. Similarly, we observed medium- (10^1–10^2 ha) to large-sized (10^3 ha) patches of stand initiation structure, which in our experience reflected prior stand replacement disturbance rather than fire exclusion or grazing. Moreover, old, park-like or similar ponderosa pine stand structures did not dominate the landscapes, and this was particularly perplexing because this was to be the signature outcome of frequent low severity fires.

Research objectives

Wildfire effects are known to be spatially heterogeneous (Agee 1993, 1998, 2003; Fulé et al. 2003; Swetnam and Baisan 1996); patterns of severity vary with gradients of topography, vegetation, and climate (Agee 1993; Rollins et al. 2002), and with the complexity and interactions among disturbances over space and time. Despite awareness of interrelations between patterns of severity and landscape conditions, little has been done to characterize spatio-temporal patterns and variation in historical fire severity (Ehle and Baker 2003; Baker et al. 2007). Methods too have been lacking to characterize all but the least and most severe of fires (Fulé et al. 2003; Johnson and Miyanishi 2001), and this has limited progress. Here, we take a structural approach to estimating pre-management era fire severity area and patch size distribution in mixed conifer forests of eastern Washington, USA. Objectives were: (1) to classify for patches of censused landscapes, the most likely severity of the last fire; and (2) to quantify and compare abundance and severity of patches for cover types, structural classes, and dry and moist forest potential vegetation types. We show trends in pre-management era fire severity by potential vegetation type, cover type, and structural class. Potential vegetation types were used to bin forested patches and evaluate the premise that dry forests were mostly visited by low severity fires.

Methods

Assumptions

We used pre-management era (ca.1900) overstory and understory canopy cover, size class, and cover type to classify the most likely severity of the last fire for each patch in the landscape. In method development, we assumed: (1) total canopy cover of a patch reasonably approximated potential site occupancy; (2) overstory canopy cover of a patch represented the area of the oldest cohorts remaining after the last major disturbance; (3) understory canopy cover represented the area of the newest cohorts establishing after the last major disturbance; (4) other disturbances may mix with fire, but fires caused most stand replacement disturbance and initiated most new cohorts; and (5) biophysical gradients influenced canopy cover, size class, and cover type, but fire effects were most influential.

Uncertainties

We relied on the premise that fire was the principal disturbance and we could not rule out other disturbances. There were two scales where this was important: the stand or patch scale (we use these interchangeably), and that of the landscape mosaic. Historical forest insect outbreaks have caused significant mortality (e.g., see Weaver 1961 and related work of Williams and Babcock 1983), were generally well documented, and where affecting a large area, salvage logging typically followed. This logging activity was readily detected and recorded in this dataset. At a patch scale, where insect mortality was a consequence of past wildfire, we pooled this mortality with other first order fire effects. Without special methods, nearly all fire history studies include bark beetle mortality because bark beetle contributions are difficult to reliably extract from data. Forest diseases were also relevant at this patch scale, but disease progress, even where disease is widespread (e.g., dwarf mistletoes, 40–50% incidence, Bolsinger 1978), is slow and incremental. Forest disease effects were included in our fire severity estimates, but we believe the contributed error was small and canceling because many major mortality-causing forest diseases tend to be diseases of the site.

Our method assumes that fire exclusion influences (grazing, roads, fire suppression, urban/rural development) and succession had little effect on our historical fire severity classification. This assumption is probably incorrect, but the magnitude of the uncertainty is difficult to gauge. We used a classification approach that considered the fire tolerance, size, and percentage of the overstory remaining to minimize confusion associated with succession or fire exclusion influences. However, since overstory canopy percent is computed as the ratio of the overstory canopy cover to the total tree cover as viewed from above, some influence must occur.

Study area

We used a published ecoregionalization of the Interior Columbia basin (Hessburg et al. 2000b), and selected three Ecological Subregions (ESRs) where dry and moist forests were abundant. The selected Subregions were ESR5, ESR11, and ESR13 (Fig. 1). ESR5 was the ‘‘Warm’’ (5–9°C annual average temperature), ‘‘Moderate Solar’’ (250–300 W/m^2 annual average daylight incident shortwave solar radiative flux), ‘‘Moist’’ (400–1,100 mm/year total annual precipitation), Moist and Cold Forests (predominantly occupied by moist and cold forest potential vegetation types) Subregion, but subwatersheds included dry forests. ESR11 was the ‘‘Warm’’, ‘‘Moderate Solar’’, mixed ‘‘Dry’’ (150–400 mm/year total annual precipitation) and ‘‘Moist’’, Dry and Moist Forests Subregion, and was composed of extensive mixed conifer forests occurring between grasslands or shrublands and cold forests. ESR13 was the mixed ‘‘Warm’’ and ‘‘Cold’’ (0–4°C annual average temperature), ‘‘Moderate Solar’’, ‘‘Moist’’, Moist Forests Subregion, and is composed of moist mixed and other cool/moist conifer forest potential vegetation types (e.g., *Tsuga heterophylla, Thuja plicata, and Abies amabilis*) with dry forests in the lowest elevations. In the eastern Washington, ESR11 is the domain of the archetypal dry forests.

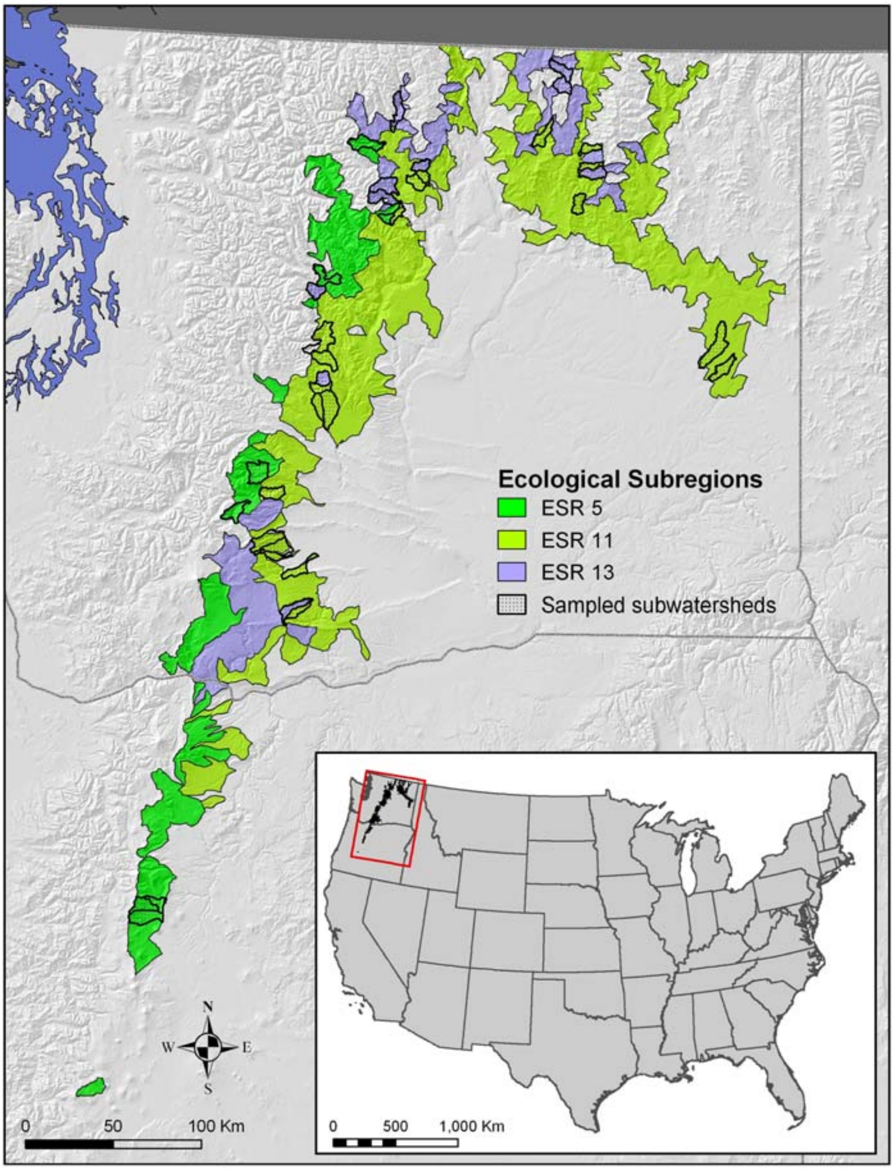


Fig. 1 Ecological subregions and subwatersheds sampled in the study area in eastern Oregon and Washington, USA, (adapted from Hessburg et al. 2000b)

Stratification by geoclimatic region

We used an existing vegetation dataset developed for the Interior Columbia Basin Project (Hessburg, et al. 1999a, 2000c, http://www.fs.fed.us/pnw/pubs/gtr_458.htm). Vegetation data were spatially continuous across sampled subwatersheds (the 6th level in the USGS watershed hierarchy, Seaber et al. 1987) and the sample frame was originally obtained using a two-stage, stratified, random sample of all subwatersheds in the Interior Columbia basin. Study area subwatersheds ranged from about 4,000 to 20,000 ha and were post-stratified by ESRs. The resulting set included 38 subwatersheds, representing about 10% of the total subwatersheds and area of each Subregion (area sampled = 303,156 ha).

Photo-interpreting vegetation attributes

The vegetation attributes of every patch in each study subwatershed were photo-interpreted from the oldest available, stereo, aerial photography (1930–1940s; photo scales: 1:15,840–1:26,000, B + W). Attributes included the total tree canopy cover (overstory + understory $\leq$ 100%); overstory canopy cover, species composition, and size classes; understory canopy cover, species composition, and size classes; number of canopy layers; percentage of canopy cover dead or as snags; and type of prior logging entry. A new patch was delineated with a single class difference of one attribute between two adjacent patches [e.g., 80% vs. 90% overstory cover, or pole- vs. small-sized understory trees]. To complete the project with available resources, a minimum patch size of 4 ha was adopted. Preliminary studies indicated that without a minimum patch size, many would be <4 ha, similar to what White (1985) found in the southwestern US. The resulting patch sizes ranged from 4 to 3, 373 ha in a negative exponential distribution; average size was 54 ha; there were 5, 741 total patches, and 88% of the patches were <100 ha.

Detecting early selection cutting

Visual cues used by photo-interpreters to detect logging included the presence of old forest road or railroad beds, skid roads connecting to stands, skid trails connecting to canopy gaps, and ground and vegetation disturbance. Single tree selection cutting was detected in many old photos but was generally absent in photos lacking roads or rails. Because the selection cutting targeted large trees (>63.5 cm d.b.h.), their removal left canopy gaps along with ground and vegetation disturbance, and skid trails as heavy logs were yarded to roads or rails. Also, skid trails were constructed at high densities because log in-winching distances (usu. <200 m) were limited by the available technology. For the 38 study subwatersheds, 14.5% of the area showed evidence of logging entry, and most was light selection cutting (10.9% of the total area).

Reconstructing vegetation to pre-harvest conditions

We reconstructed the vegetation attributes of each patch showing evidence of harvesting using Moeur and Stage’s (1995) most similar neighbor inference procedure. The most similar neighbor algorithm uses canonical correlation analysis to derive a similarity function, and then chooses as a stand-in, the most similar patch from the set of patches that have detailed *design attributes* (‘local variables’), and lower resolution *indicator attributes* (‘global variables’). The most similar stand-in patch is selected by means of the similarity function which maintains the multivariate relations between the global variables and the local variables. Global variables (1-km resolution) assigned to patches were the potential vegetation type (from Hann et al. 1997); mean annual temperature, total annual precipitation, averaged annual daylight incident short-wave radiative flux (‘‘solar radiation’’, from Thornton et al. 1997); and slope, aspect northing, aspect easting, and elevation derived from a 30-m digital elevation model. Climate data were from the year 1989, which Thornton et al. (1997) considered to be an average weather year for the region. Local variables were the photo-interpreted total and overstory canopy cover, canopy layers, size class of the overstory and understory, and overstory and understory species of the patch, which were also the attributes that were reconstructed for the logged patches. In analysis, we used the set of all patches in the sample of subwatersheds (unlogged + logged but reconstructed), and then compared results with those obtained using the set of unlogged patches alone to evaluate effects of vegetation reconstruction on fire severity area estimation.

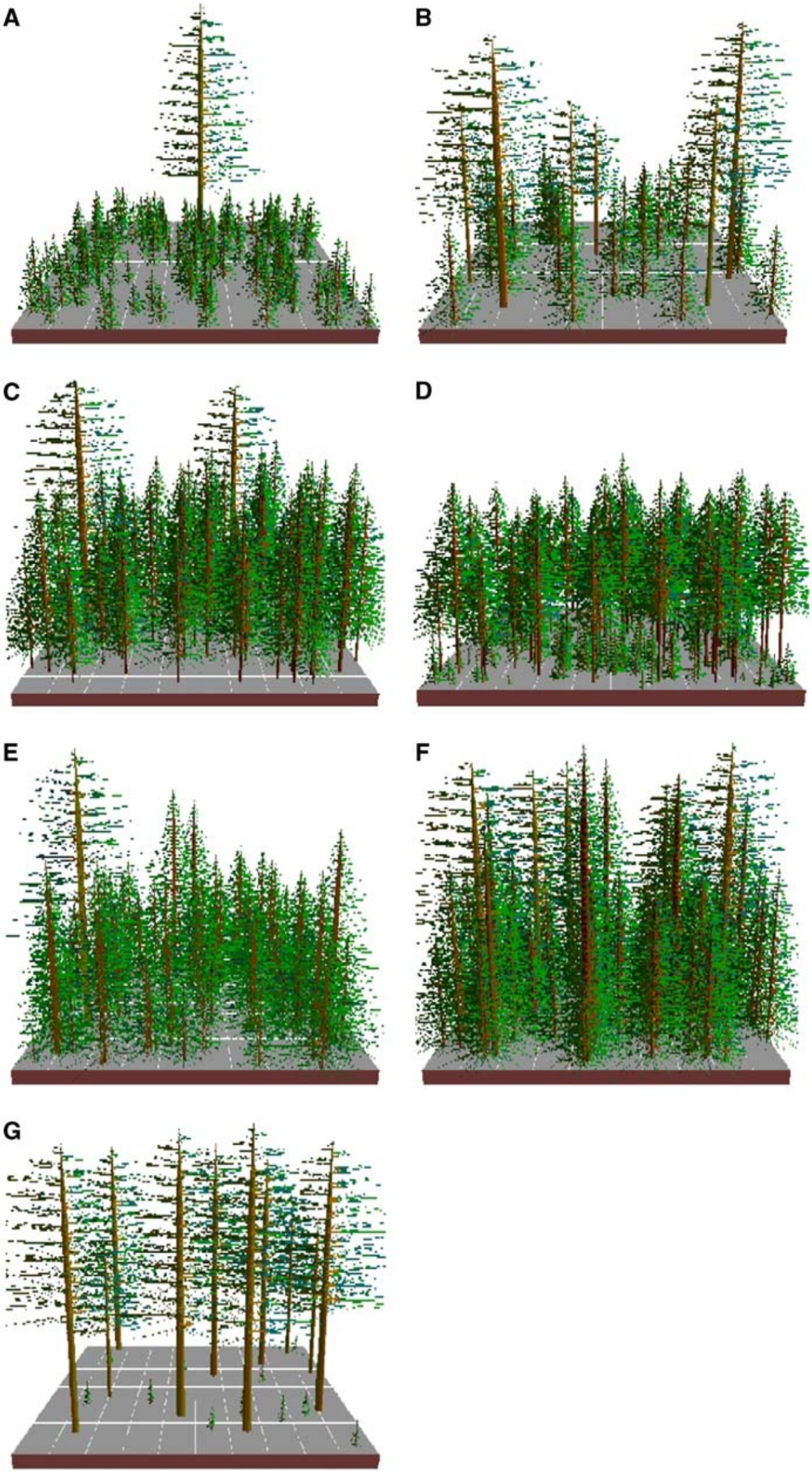
Deriving forest structural classes

Forest structural classes were derived for every patch using classification methods detailed in Hessburg et al. (1999a, 2000c) and summarized here. Figure 2(A–G) shows the structural classes that are referenced in the text, defined for Interior Northwest forests by O’Hara et al (1996), and adapted from Oliver and Larsen (1996). The classes do not represent a linear sequence in any strict sense; rather they partition a continuum of conditions resulting from stand dynamics, succession, and disturbance processes into bins representing key mileposts in stand development. Absent disturbance, the structural classes are more or less sequential; with disturbance they can be progressive or retrogressive.

Assigning the potential vegetation type

The potential vegetation type of each patch was assigned using the methods of Hessburg et al. (1999a, 2000a). We assigned a potential vegetation type to each patch to directly evaluate the premise that dry

Fig. 2 Graphic representation of derived structural classes of eastern Cascades forests: (**A**) stand initiation, (**B**) open canopy stem exclusion, (**C**) closed canopy stem exclusion, (**D**) understory reinitiation, (**E**) young multistory forest, (**F**) old multistory forest, and (**G**) old single-story forest (adapted from O'Hara et al. 1996; Oliver and Larsen 1996)



forest patches were tightly coupled with low severity fires. The most shade tolerant conifer species was identified using historical overstory and understory species composition attributes, and elevation, slope, and aspect layers generated from 90-m digital elevation models of the subwatersheds. Potential vegetation analysis was done separately for subwatersheds of each subbasin (4th level in the USGS hierarchy, Seaber et al.1987). We separated patches in the Douglas-fir/grand fir potential vegetation type into warm-dry (dry forest) and cool-moist (moist forest) subgroups using the classification rules unique to each subbasin.

Selecting a severity rating system

There are numerous fire severity rating systems in the US and worldwide; examples are given in Agee (1990, 1993, and references therein); we adopted the definitions of Agee, an authority on Inland Northwest fire ecology. Thus, low, mixed, and high severity fires were defined as destroying by fire, ≤20%, 20.1–69.9%, ≥70% of the total canopy cover or basal area of a patch, respectively.

Classifying fire severity

We classified fire severity of a patch using the overstory canopy percentage (i.e., percentage of the total that was overstory), the overstory size class, the understory size class, and the fire tolerance of the cover type (Table 1). Overstory canopy percentage represented the overstory remaining after the last fire. Overstory canopy percentage classes (= overstory canopy remaining classes, ≥80%, 30.1–79.9%, ≤30%) used to define low, mixed and high severity fires directly corresponded with published fire severity boundary values (i.e., overstory canopy removed, ≤20%, 20.1–69.9%, ≥70%, respectively, Agee 1993).

In 19% of the patches, representing 18% of the area, the fire tolerance of the cover type was also used to predict the most likely fire severity (Table 1). Cover type was used where overstory canopy percentage exceeded 80%, and where it was impossible to discern from structural attributes alone whether severity was high (stand replacing fire from a long time ago) or low (surface fire maintained). For example, when the cover type was grand fir, overstory size was small to medium trees, and overstory canopy cover was >80%, the assigned fire severity was ‘‘High’’ rather than ‘‘Low’’. This was considered the most likely prediction because the size, canopy cover and fire intolerance of the cover type suggested that high severity fire had more likely regenerated the patch some decades ago rather than high frequency and low severity fire maintaining a continuous coverage of thin-barked, fire-intolerant trees. Consistent with the fire ecology literature, severity classification explicitly assumed that thin-barked, fire intolerant species would be stand-replaced, and that thick-barked, fire tolerant species would be conserved (Table 1). Of the total cases where the cover type was used, 82% were classified to low severity fire, 18% to high severity fire.

Statistical analysis

The study entailed a complete census of conditions in 38 subwatersheds. To broaden the scope of inference, we applied non-parametric rank ordered tests based on the Chi-square distribution to test for significant differences in area of a fire severity class by cover type, potential vegetation type, Subregion, and study area. We used Society of American Foresters cover type definitions (Eyre 1980) to represent actual vegetation cover (http://www.fs.fed.us/pnw/pubs/gtr_458.htm). We used the Kruskal–Wallis *H*-test to compare observed and expected area in fire severity classes of ponderosa pine or Douglas-fir cover types in dry or moist forest, within and among Subregions, and for the study area. Significant difference ($P \leq 0.05$) was evaluated using the Mann–Whitney *U* pairwise post-hoc comparison procedure. The Mann-Whitney U-test was also used to compare area in fire severity classes of ponderosa pine and Douglas-fir cover types, and area within severity classes by potential vegetation type within Subregions, and for the study area (Tables 2, 3).

Results

Mixed severity fires were most prevalent across all forest types of the three Subregions; low, mixed, and high severity fires occurred on 16, 47, and 37% of total forest area, respectively.

Table 1 A dichotomized key to fire severity classification

1a. Patch is not forested	
2a. Patch is rangeland	High severity
2b. Patch is non-rangeland	No severity
1b. Patch is forested	
3a. Overstory size class $\geq$ small trees and understory size class $\leq$ small trees[a]	
4a. Overstory canopy percent $\geq$80%	
5a. Cover type is not fire tolerant[b]	High severity
5b. Cover type is fire tolerant[c]	Low severity
4b. Overstory canopy percent < 80%	
6a. Overstory canopy percent $\leq$30%	High severity
6b. Overstory canopy percent >30%	Mixed severity
3b. Overstory size class < small trees or understory size class > small trees	
7a. Overstory size class < small trees	High severity
7b. Understory size class > small trees	
8a. Overstory canopy percent $\leq$ 30%	High severity
8b. Overstory canopy percent > 30%	
9a. Overstory canopy percent $\geq$ 80%	
10a. Cover type is not fire tolerant	High severity
10b. Cover type is fire tolerant	Low severity
9b. Overstory canopy percent <80%	Mixed severity

[a] Photo-interpreted tree size classes are: seedlings and saplings (<12.7 cm d.b.h.), poles (12.7–22.6 cm d.b.h.), small trees (22.7–40.4 cm d.b.h.), medium trees (40.5–63.5 cm d.b.h.), and large trees (>63.5 cm d.b.h.)

[b] Fire tolerant cover types of the study area are: ponderosa pine (PIPO), western larch (LAOC), Interior Douglas-fir (PSME), western white pine (PIMO), and sugar pine (PILA)

[c] Fire intolerant cover types of the study area are: lodgepole pine (PICO), grand fir (ABGR), white fir (ABCO), Pacific silver fir (ABAM), subalpine fir (ABLA2), Engelmann spruce (PIEN), western hemlock (TSHE), western redcedar (THPL), mountain hemlock (TSME), Whitebark pine (PIAL), subalpine larch (LALY), and all hardwoods

Fire severity by Subregion

In ESR5, mixed severity fires were found on 55% of the total forest area; the remainder was unevenly split between low (13%) and high severity (32%) fires. ESR11 showed the greatest area in high severity fires with 46%; mixed severity fires comprised 39%, while low severity fires comprised 15% of the forest area. Mixed severity fires dominated ESR13 (53%), the remainder was evenly split between low (21%) and high severity (26%) fires.

Severity by forest structural class

In general, forest structure pointed to highly variable mixed severity fire as the prevailing fire process. Forest structure was dominated by intermediate-aged patches consisting of young multistory forest ‘‘yfms’’, understory re-initiation ‘‘ur’’, and open canopy stem exclusion structures ‘‘seoc’’ (O’Hara et al. 1996, Fig. 3). In ESR11, most area influenced by low severity fire fell within the open canopy stem exclusion structure, with the balance falling in the young multi-story, understory re-initiation, stand initiation ‘‘si’’, and old single story ‘‘ofss’’ forest structures (Fig. 3). The dominant fire severity was mixed, even in old single and multi-story ‘‘ofms’’ structures.

Similarly, in ESR13 old multistory structure was widespread; forming the 4th most dominant feature, but mixed rather than low severity fire was associated (Fig. 3). In ESR5, most low severity fire occurred in open canopy stem exclusion structures with only a fraction (1.5% of the area) occurring in old single story structures. Open canopy stem exclusion structures were comprised of the ponderosa pine cover

Table 2 Kruskal–Wallis *H*-test comparing area in a fire severity class of ponderosa pine or Douglas-fir cover types, and by pooled cover type, within three Ecological Subregions, and for the study area

Subregion	Cover type	Fire severity class post-hoc comparison	Area (ha)	χ^2-value	*P*-value
ESR5	Ponderosa pine	Low	5,106	1.043	0.594
		Mixed	9,931		
		High	5,821		
	Douglas-fir	Low	2,904	2.869	0.238
		Mixed	11,372		
		High	3,606		
	Pooled	Low	8,010	2.686	0.261
		Mixed	21,303		
		High	9,427		
ESR11	Ponderosa pine	Low a	16,203	9.654	**0.008**
		Mixed a	33,460		
		High a	5,798		
	Douglas-fir	Low	5,685	3.836	0.147
		Mixed	17,656		
		High	8,498		
	Pooled	Low a	21,888	12.096	**0.002**
		Mixed a	51,116		
		High a	14,297		
ESR13	Ponderosa pine	Low a	10,071	15.558	**0.0004**
		Mixed a	18,612		
		High a	1,380		
	Douglas-fir	Low	4,720	2.520	0.284
		Mixed	12,686		
		High	5,391		
	Pooled	Low a	14,791	15.194	**0.001**
		Mixed b	31,298		
		High a	6,771		
Study area	Ponderosa pine	Low a	31,380	20.852	**0.0003**
		Mixed a	62,003		
		High a	13,000		
	Douglas-fir	Low a	13,310	9.467	**0.009**
		Mixed b	41,714		
		High a	17,495		
	Pooled	Low a	44,690	28.851	**0.0002**
		Mixed b	103,717		
		High a	30,495		

Values in bold significantly differ ($P \leq 0.05$) in area (ha) of a fire severity class. Severity classes followed by the same letter are not significantly different according to Mann–Whitney *U*-test pairwise post-hoc comparisons

type in all Subregions, accounted for most of the low severity fires, and came closest to resembling historical descriptions of park-like pine stands, but they were not dominated by large trees. Where large trees were present, they formed a remnant overstory representing less than 30% of total canopy cover.

Severity by forest cover type

Across the study area, ponderosa pine and Douglas-fir cover types provided most of the forested land cover, pine cover was most prevalent, most low severity fire occurred in ponderosa pine and Douglas-fir cover types, and of these, the greatest share

Table 3 Kruskal–Wallis *H*-test comparing area in a fire severity class of dry, moist, and pooled potential vegetation type, within three Ecological Subregions, and for the study area

Subregion	Potential vegetation type	Fire severity class post-hoc comparison	Area (ha)	χ^2-value	*P*-value
ESR5	Dry forest	Low a	3,712	6.794	**0.033**
		Mixed b	10,414		
		High a	6,008		
	Moist forest	Low	1,278	0.717	0.699
		Mixed	13,827		
		High	5,482		
	Pooled (Dry + Moist)	Low a	4,990	6.258	**0.044**
		Mixed a	24,242		
		High a	11,490		
ESR11	Dry forest	Low a	12,019	11.777	**0.003**
		Mixed b	33,853		
		High a	12,559		
	Moist forest	Low a	3,124	38.554	**0.0001**
		Mixed b	15,054		
		High a	6,742		
	Pooled	Low a	15,142	42.048	**0.0001**
		Mixed b	48,906		
		High c	19,301		
ESR13	Dry forest	Low a	8,470	24.878	**0.0001**
		Mixed b	21,452		
		High a	3,630		
	Moist forest	Low a	3,845	6.451	**0.04**
		Mixed a	9,307		
		High a	4,392		
	Pooled	Low a	12,315	28.405	**0.0001**
		Mixed b	30,758		
		High a	8,021		
Study area	Dry forest	Low a	24,200	40.940	**0.0001**
		Mixed b	65,719		
		High a	22,196		
	Moist forest	Low a	8,247	42.291	**0.0001**
		Mixed b	38,187		
		High c	16,616		
	Pooled	Low a	32,447	78.681	**0.0001**
		Mixed b	103,906		
		High c	38,812		

Values in bold significantly differ ($P \leq 0.05$) in area (ha) of a fire severity class. Severity classes followed by the same letter are not significantly different according to Mann–Whitney *U*-test pairwise post-hoc comparisons

occurred in the pine cover type, but mixed severity fires dominated both types (Fig. 4). In ESR11, ponderosa pine cover was dominant over Douglas-fir almost 2:1, and most area influenced by low severity fires occurred in the pine cover type; suggesting a possible landscape effect of severity dampening via a relatively more fire tolerant actual vegetation cover. However, Mann–Whitney *U*-tests showed that there was no difference in the area of fire severity class between the ponderosa pine and Douglas-fir cover types of any Subregion, or for the study area. In essence, ponderosa pine and Douglas-fir functioned as one cover type with respect to fire severity.

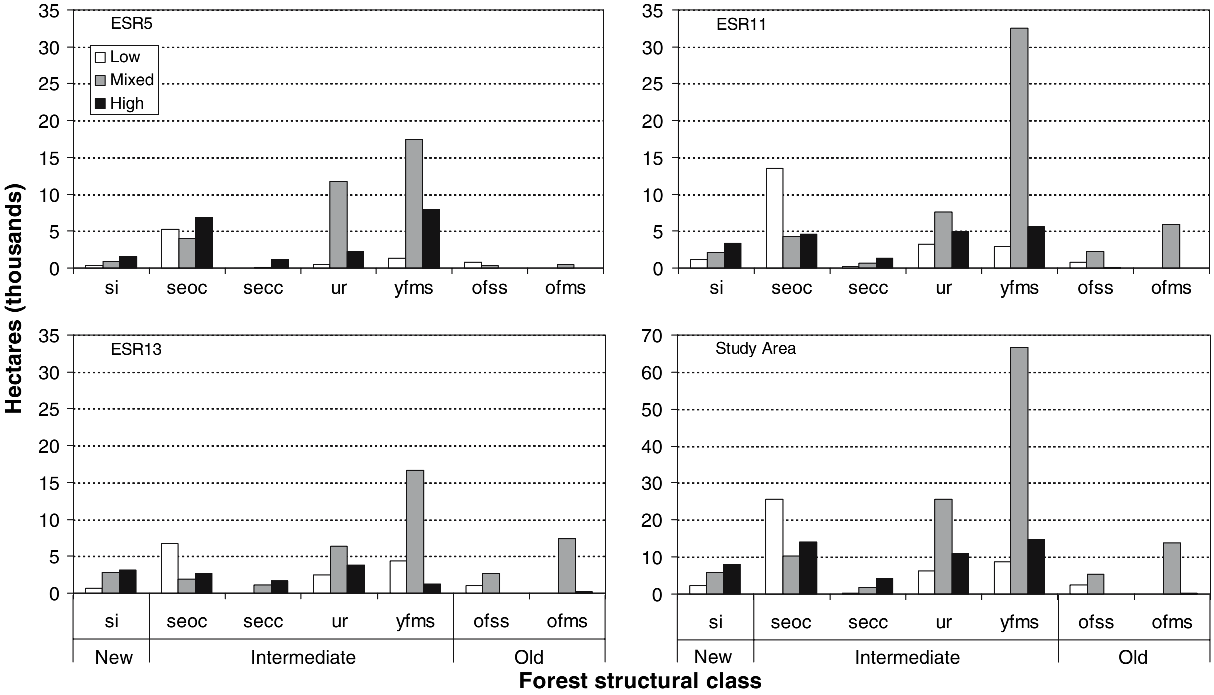


Fig. 3 The proportions of the pre-management era dry forest area (ha) by forest structural class in low, mixed, and high severity fire (corresponding with percent canopy mortality values of $\leq$20%, 20.1–69.9%, $\geq$70%, respectively) of Ecological Subregions 5, 11, and 13. Structural class abbreviations are: si = stand initiation, seoc = open canopy stem exclusion, secc = closed canopy stem exclusion, ur = understory reinitiation, yfms = young multistory forest, ofms = old multistory forest, ofss = old single-story forest. New, intermediate, and old designations are used to group structural classes into broad age groups

We also tested for significant difference in area of fire severity classes within a cover type of a Subregion. Kruskal–Wallis tests showed that there were weak differences in area of fire severity classes of either the ponderosa pine or the Douglas-fir cover type of a Subregion (Table 2), however, for the study area; the test showed a significant difference within the Douglas-fir cover type and for pooled cover types. Mann–Whitney *U*-tests showed that area of mixed severity fire was greater (P = 0.009 and 0.0002, respectively) than the areas of either low or high severity fire.

Severity by potential vegetation type

We tested whether fire severity class area was evenly distributed in the dry and moist forests using the Kruskal–Wallis *H*-test (Table 3). We found that class areas were significantly different in the dry and moist forests of all Subregions and the study area, with one exception; area by fire severity class was not different in moist forests of ESR5 (P = 0.699). When we pooled the dry and moist forests, we found for all Subregions and the study area that severity class areas were also different (Table 3); for the most part, fire severity was unevenly distributed. In nearly all cases, the area affected by mixed severity fires was greater than that of either low or high severity fires. In many cases, the area of low severity fire did not differ from that of high severity fire. This was not the case for the study area, where all severity classes areas of the moist forest and pooled types were different (P = 0.0001).

Next, we pairwise compared fire severity class area of the dry and moist forests of Subregions and the study area. Potential vegetation types did not differ by fire severity class area with two exceptions; in these, area in the high severity class of ESR11 was two-fold greater (P = 0.001) in the dry than moist

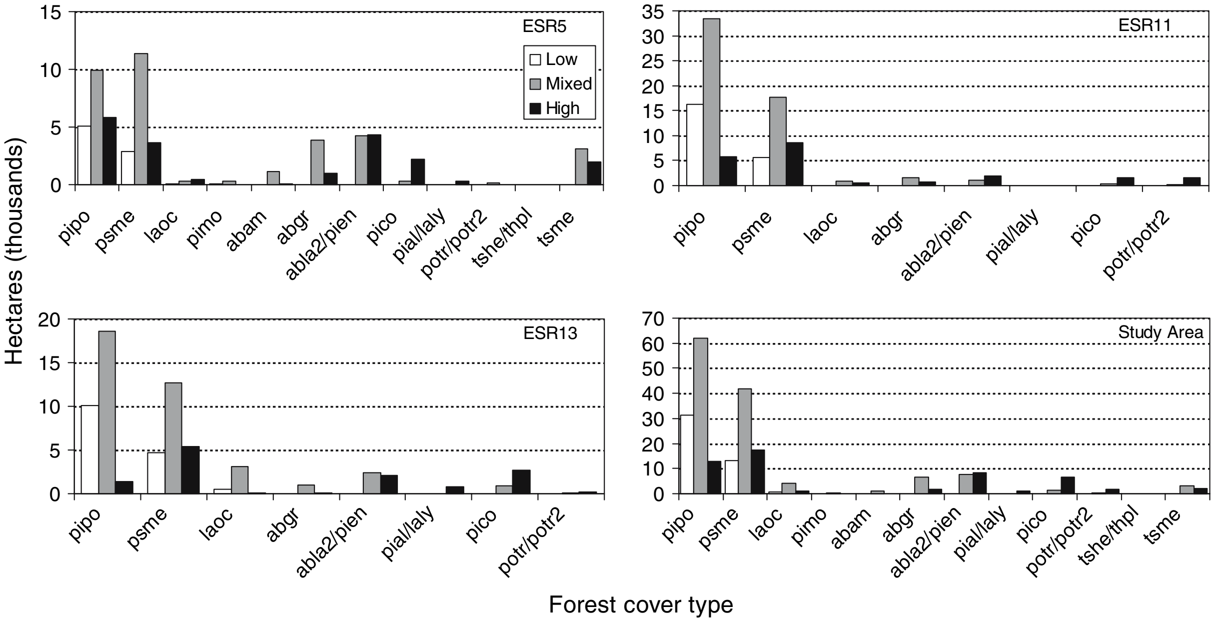


Fig. 4 The proportions of pre-management era total forest area (ha) by forest cover type in low, mixed, and high severity fire (corresponding with percent canopy mortality values of ≤20%, 20.1–69.9%, ≥70%, respectively) of Ecological Subregions 5, 11, and 13. Cover type abbreviations are: tshe/thpl = western hemlock/western redcedar; pimo = western white; potr/potr2 = *Populus* and *Salix* spp.; laoc = western larch; tsme = mountain hemlock; pial/laly = whitebark pine/subalpine larch; abam = Pacific silver fir; abgr = grand fir; pico = lodgepole pine; abla2/pien = subalpine fir/Engelmann spruce; psme = Douglas-fir; pipo = ponderosa pine

forests; likewise for the study area, high severity class area was 34% greater (*P* = 0.008) in the dry than moist forests.

Finally, we compared Subregion fire severity class area of dry, moist, and pooled types using the Kruskal–Wallis *H*-test. In moist forests, ESR11 had more high severity fire area than either ESRs five or 13 (*P* = 0.001). Similarly, for the pooled types, the Kruskal–Wallis test showed that there were differences in the area of high severity fire among the Subregions (*P* = 0.018), but Mann–Whitney post-hoc comparisons were unable to separate them due to variation. Most of the low severity fire occurred in the dry forests, but mixed fire severity was most pervasive within each Subregion and across the study area. For example, in ESR5, 18% of the total area in the dry forest type was influenced by low severity fire; 52% by mixed severity, and 30% by high severity fire. In the moist forest type, corresponding values were 6, 67, and 27%, respectively, and no difference was significant (Fig. 5). In ESR5, there was three-fold more area affected by low severity fires in the dry than in the moist forest type, but the difference was not significant (*P* = 0.772). Across the study area, 22% of the area in the dry forest was affected by low severity, 59% by mixed severity, and 20% by high severity fire; while in moist forest, values were 13, 61, and 26%, respectively, and no difference was significant (Fig. 5).

Variability of mixed severity fire

For all dry forest patches of each Subregion, and the study area that were influenced by mixed severity fire, we plotted the percentage area in 10% overstory canopy cover classes (Fig. 6). In ESR11, 43% of the area displayed an overstory canopy percentage >51%, indicating that the last fire, even though technically of mixed severity, looked more like low severity fire in the aftermath, because most overstory trees survived, and surface fire effects dominated over stand replacement. Considering together area influenced by low and mixed severity fires, with the majority of trees remaining, 63% was affected by surface fire dominated regimes; the balance (37%) was influenced by stand replacement dominated regimes. In ESRs 5 and 13, 41 and 35% of the area in mixed severity fire displayed an overstory canopy percentage >51%. Across the study area, 40% of the dry forest area showing mixed severity fire displayed >51% overstory canopy remaining in the oldest cohorts (Fig. 6). Considering the area affected by low and mixed severity fires (with the majority of trees remaining), 62% was affected by surface fire dominated regimes (those where tree torching and crowning fire are relatively minor features); the balance (38%) was affected by stand replacement fire dominated regimes. Hence, our results suggest that pre-management era fires of dry forests were strongly surface fire dominated but coming from both low and mixed severity fires. There were no significant differences among Subregions ($P > 0.05$) in these relations.

We repeated this analysis for moist forest patches of the Subregions and the study area. In ESRs 5, 11, 13, and for the study area, 35, 55, 37, and 43% of the area in mixed severity fire displayed an overstory canopy percentage >51%, respectively. Considering together area affected by low and mixed severity fires, with the majority of trees remaining, 46% were affected by surface fire dominated regimes; the balance (54%) were affected by stand replacement fire dominated regimes. Thus, fires of moist forest patches tended to be stand replacement fire dominated coming from both mixed and high severity fires.

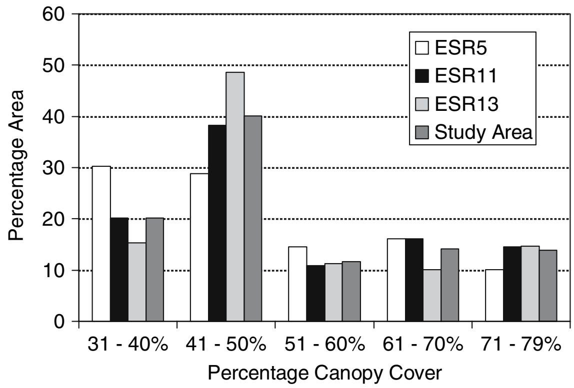


Fig. 6 The percentage of the total area of the dry forest potential vegetation type that was last affected by mixed severity fire (MSF) in 10% overstory canopy cover classes of Ecological Subregions 5, 11, and 13, and the study area. The overstory canopy percentage is the ratio – (overstory canopy cover/total canopy cover) × 100

Influence of the vegetation reconstruction

In all analyses reported thus far, we used the set of all patches in the censused subwatersheds (unlogged + logged but statistically reconstructed). We reran all reported analyses using the set of unlogged patches alone to evaluate effects of vegetation reconstruction on estimated abundance of fire severity. We found no significant differences in relations of fire severity class abundance to cover types, structural classes, or potential vegetation

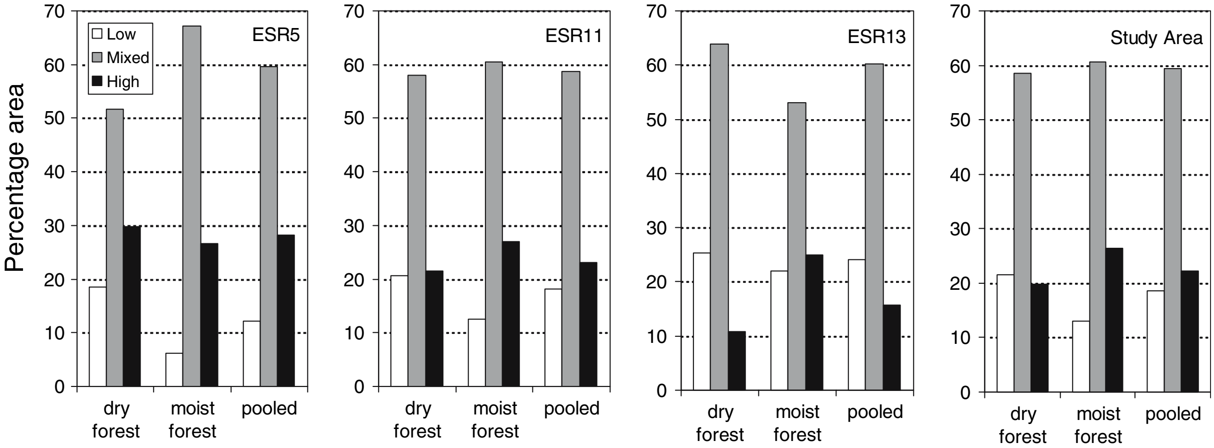


Fig. 5 The proportions of the pre-management era forest area (ha) by forest potential vegetation type in low, mixed, and high severity fire (corresponding with percent canopy mortality values of ≤20%, 20.1–69.9%, ≥70%, respectively) of Ecological Subregions 5, 11, and 13, and the study area. Comparisons are shown for the dry and moist forest potential vegetation types, and pooled (sum of dry + moist)

types of any Subregion, or the study area, however, reconstructions replaced the large trees removed by selection cutting. This increased total hectares of old forest, number and area of young and intermediate-aged patches with remnant large trees in their overstory, area of the ponderosa pine cover type, and amount of low severity fire overall. We use the reconstructed data in all analysis because it best represented the natural variation of pre-management era fire severity and vegetation conditions.

Discussion

Pre-management era fire severity and forest structure

The observation of abundant intermediate-aged forest patches is quite revealing. We suspected that the most similar neighbor reconstructions, by replacing harvested trees, would increase the likelihood of observing low severity fires. However despite reconstruction, much intermediate-aged forest was observed. Examining the set of reconstructed patches, we noted that the algorithm did a good job of reconstructing old forest patches as well as those with remnant large trees.

When formulating the study, we hypothesized that where stable equilibria were operating, those patches would be dominated by persistent, stable structures featuring old, fire-tolerant park-like or similar stands, as the literature suggested. Instead, area was dominated by forest structures that were intermediate between new and old forests, i.e., by pole to medium-sized, rather than large trees (Table 1 and Fig. 3). This observation suggested that before any extensive management had occurred, the influence of fire in the dry forest was of a frequency and severity that intermittently regenerated rather than maintained large areas of old, fire tolerant forest.

We also observed a preponderance of the low severity fires in open stem exclusion structures (Fig. 3); this was an important observation. Open stem exclusion structures could be maintained by high frequency, low severity fires and become relatively stable structures, with time, moving directly into old single story, park-like forest; or they could be shunted along other structural paths where fire frequency and severity were otherwise. Perhaps these were antecedent conditions of park-like stands described in early fire history studies.

Potential bias in point and area-based estimates

We acknowledged earlier that point sampling of recorder trees potentially overestimates likelihood of low severity fires and underestimates mixed and high fire severity. Similarly, area based methods can overestimate the likelihood of mixed and high severity fires, and underestimate low severity fire (e.g., see discussion in Minnich et al. 2000; Stephens et al. 2003). For this reason, we suggest coupling of point and area estimates in future fire history studies; point observations would register events for which recorder trees remain, and distribute them spatially; understory cohorts could be sampled and aged across the same landscape to determine whether they were initiated in response to events registered on the set of surviving recorder trees, or in response to other events not represented by the recorders. Pairing of point and area samples would also significantly improve spatial accuracy of severity mapping.

Non-equilibrium fire dynamics in the pre-management era

Several lines of evidence point to non-equilibrium rather than equilibrium dynamics in pre-management era mixed conifer forests. First is the coupled occurrence of low, mixed, and high severity fires with young and intermediate-aged forest structures. Equilibrium dynamics would be represented by the coupled occurrence of low severity fires and old, multi-cohort, fire tolerant, park-like or similar stands; we did not find these conditions in abundance. Second, highly variable mixed severity fires (Figs. 5 and 6) dominated all Subregions and the study area. Even when considering old multi-story or single story forest structures in isolation, most old forest area was apparently under the influence of mixed rather than low severity fire. It is noteworthy that nearly two-thirds (62%) of study area dry forests were influenced by surface fire dominated regimes; while fewer than half (46%) of moist forests were so affected. This observation is helpful in explaining why fire history studies in dry forests that employ point sampling tend to couple such forests with low severity fire.

Third, there were few differences in area influenced by a fire severity class between the dry and moist forests. Mixed fire severity was the primary influence throughout the mixed conifer forest; surface firing tended to increase when fires affected drier topo-edaphic settings and decrease in moist and cool settings. This stands to reason; dry and moist forests typically occur in adjacent biophysical settings, often separated by short distance, and elevation and aspect differences that can be minimized during the heat and drought of a summer fire season.

Fire severity in ecotonal ponderosa pine potential vegetation types

We applied the identical fire severity classification methods to all patches of the dry ponderosa pine potential vegetation type throughout the study area. We found that these patches were tightly coupled with low severity fire regimes; low, mixed, and high severity fires affected 66, 21, and 13% of the dry ponderosa pine patches in the study area, respectively.

Here, we forward an alternative hypothesis concerning equilibrium disturbance dynamics of dry forests. Low severity fires and equilibrium dynamics likely occurred in eastern Washington dry forests, where they fostered fire tolerant, park-like pine stands, however, these dynamics were perhaps ephemeral in nature, lasting one or more centuries at a location, and then switching concordant with regional climate forcing to non-equilibrium states. The similarity in fire severity among patches in dry and moist mixed conifer types may in fact be related to regional climatic extremes that override a tendency for moist types to generally experience more severe fire (Schoennagel et al. 2004).

Potential vegetation types as a proxy for historical fire severity

In addition to top–down biogeoclimatic controls, there is likely bottom-up topo-edaphic control of pre-management era and present-day fire severity, but the potential vegetation type poorly explained this relation in mixed conifer forests in eastern Washington. There has been a strong tendency to use the potential vegetation type as a surrogate for the vector of unknown environmental variables that controls fire severity. This was probably done for at least two reasons: (1) it is intuitive that the potential vegetation type might integrate and reflect the biophysical factors responsible for bottom-up spatial controls; and (2) foresters and fire scientists interested in landscape restoration need a method to spatially distribute historical and present-day fire disturbance and its effects in order to simulate spatio-temporal patterns and variation in forest structure and composition (e.g., see Chew 1997; Hann et al. 1997; Keane et al. 1998, 1999, 2002). These reasons aside, we suspect that any vector of purely environmental variables will fall short as a useful surrogate for fire severity because such patterns are inherently noisy and influenced by processes with strong stochastic elements. Schoennagel et al. (2004) used Küchler's PNV groups to summarize relations in the Rocky Mountains (Küchler 1964, 1975). While related to the potential vegetation type, they are sufficiently different in concept to function well in generalizing correspondence between fire regime and vegetation type. Recall that Küchler's types define what will occur in an environmental setting considering the natural disturbance regimes, soils, climate, and topography.

Pre-management era and present-day fire severity

Many today believe that fire severity in present-day dry forests throughout the West is unprecedented. Indeed, the impetus behind the Healthy Forests Restoration Act (HFRA, U.S. Government 2003) is the idea that the structures, habitats, and disturbance regimes of present-day western dry forests are inconsistent with pre-management era conditions. There is credible scientific evidence to back up much of that claim; landscape evaluations conducted in the western US point to anthropogenic causes along with climatic signal shifting (e.g., Brown et al. 2004; Hessburg et al. 2005; SNEP 1996; Whitlock and Knox 2002). However, the HFRA tacitly incorporates a notion that dry forests of the western US are synonymous with frequent low severity fires, and that conditions supporting such fires should be widely restored. The evidence for this latter assertion is less well established. Our results suggest that low, mixed, and high severity fires each occurred in dry (and moist) mixed conifer forests of eastern Washington. The scope of management and restoration activities could be broadened to not only accept many such wildfire effects, but to manage for them. This should be good news for forest managers because it suggests that some contemporary wildfire effects will meet management objectives, and a broader suite of forest structural conditions and a broader range of patch sizes supported native fire regimes of mixed conifer forest.

Mounting evidence for variable fire severity

Schoennagel et al. (2004) review an extensive literature concerning pre-management era fire regimes of Rocky Mountains forests from Montana to New Mexico, including mixed conifer forests. They show strong evidence of variable fire severity in those types, but indicate that mixed conifer systems were probably dominated by mixed severity fires. Similarly, Baker and Ehle (2001), Ehle and Baker (2003), and Baker et al. (2007) show evidence for variable fire severity in ponderosa pine and Douglas-fir forest types.

Management implications

Spatio-temporal patterns of living and dead trees influence the likelihood of crowning fire, fire spread rate, flame length, and fireline intensity at patch to landscape scales (Agee et al. 2000; Baker 1989, 1992, 1993, 1994; Huff et al. 1995; Shinneman and Baker 1997). Landscape evaluations clearly show that many Inland Northwest forest landscapes have undergone extensive change in spatial patterns of living and dead vegetation (Agee 1998, 2003; Hessburg et al. 1999b, 2000c, 2005; Schoennagel et al. 2004). When changes to a warmer, drier climate are considered (Heyerdahl et al. 2002; Whitlock et al. 2003) the likelihood of large, high-severity fires has increased over the last century (Agee 1998, 2003; Hessburg and Agee 2003; Hessburg et al. 2005), and will continue to increase in the next. In some dry forest systems, settlement and management have created contagious vegetation patterns prone to unrestricted fire spread. In others, development has fragmented landscapes dissected by roads and housing, where opportunities for accidentally-caused fires have increased. In contrast, historical dry forest landscapes represented a relatively complex patchwork of fire regimes and patch sizes; an imprint that is often difficult to see today (Hessburg et al. 2005).

Restoring resilient forest ecosystems will necessitate managing for more natural patterns and patch size distributions of forest structure, composition, fuels, and fire regime area, not simply a reduction of fuels and thinning of trees to favor low severity fires. In shorthand, to enable occurrence of the fire regimes of interest, spatial and temporal patterns of vegetation and fuels that will support them are needed. More natural historical patterns of Inland Northwest structure, composition, and fuels can be distinguished from empirical estimates of pre-management era range and variation (e.g., Allen et al. 2002; Hann et al. 1997; Hessburg et al. 1999b, 1999c, 2000c, 2004), and via projections from succession and disturbance simulation models (e.g. Chew 1997; Keane et al., 2002; Kurz et al. 2000). If the management goal is to produce resilient forest ecosystems, it will be important to re-establish a coupling like that which existed between native landscape patterns of forest vegetation and fuels, and the native patterns and patch size distributions of fire regimes. Considering the contemporary climate and each future shift in climatic regime, it will be important to forge evolving concordance between landscape patterns of forest vegetation and fuels, and the patterns and patch size distributions of fire regimes that would be expected under each new climatic regime.

As we state in the *Introduction*, the mixed severity fire bin is large, spanning fires that range from surface to crown fire dominated. Leaving the existing mixed severity fire class intact probably has limited utility. Instead, it would be useful to managers if fire and landscape ecologists explored the mixed severity fire continuum and erected finer classes reflective of the comparative roles of surface and stand replacing fires, thereby giving managers more insight about how they might vary and distribute management intensities.

Conclusions

We have shown in eastern Washington mixed conifer forests that the distribution of fire severity among patches in the dry and moist mixed conifer forest was more similar than different. We found that ponderosa pine and Douglas-fir functioned as similar cover types with respect to fire severity. We expected to find strong evidence of equilibrium fire dynamics in the pre-management era dry forests and instead found evidence of variable fire severity, with mixed severity fires and what we suspect are non-equilibrium dynamics dominating. Four lines of evidence were important: (1) A persistent and stable cover of fire-tolerant old forest or similar structures did not dominate the dry forest landscape; rather it was dominated by intermediate-aged and young forest structures composed of fire-tolerant species. (2) Instead of strong dominance of low severity fires, we saw variable fire severity—a virtual continuum of mixed severity fires with lesser amounts of low and high severity fires. (3) Old forests were maintained and influenced by mostly mixed rather than low severity fires. (4) There were few quantitative differences in the area influenced by fire severity between the dry and moist mixed conifer forests. A single and important exception was that surface firing tended to increase when fires affected dry forest patches and decrease when fires affected moist forest patches.

Finally, it is not clear that most present-day fires of dry or moist mixed forests produce catastrophic results; rather, each should be evaluated on its own merits. What is apparent is that the size and intensity of modern fires may be coarsening the grain of the future forest landscape, and thereby, altering its functionality.

Acknowledgments We thank Dave W. Peterson and Richy Harrod for helpful discussions, and Bruce Rieman, Bill Romme, Jim Agee, Tom Spies, Monica Turner, Kerry Wood, Don McKenzie, and four anonymous reviewers for insightful comments. We are solely responsible for data interpretation and the conclusions. This research was funded by the National Fire Plan and USDA Forest Service, PNW Research Station-RWU-4577.

References

Agee JK (1990) The historical role of fire in Pacific Northwest forests. In: Walstad J et al. (ed) Natural and prescribed fire in Pacific Northwest forests. Oregon State University Press, Corvallis, OR, pp 25–38

Agee JK (1993) Fire ecology of Pacific Northwest forests. Island Press, Washington, DC

Agee JK (1994) Fire and weather disturbances in terrestrial ecosystems of the eastern Cascades. PNW-GTR-320. USDA, Forest Service, Portland, OR

Agee JK (1998) The landscape ecology of western forest fire regimes. Northwest Sci 72:24–34

Agee JK, Bahro B, Finney MA [and others] (2000) The use of shaded fuelbreaks in landscape fire management. Forest Ecol Manage 127:55–66

Agee JK (2003) Historical range of variability in eastern Cascades forests, Washington, USA. Landscape Ecol 18:725–740

Allen CD, Savage MS, Falk DA, [and others] (2002) Ecological restoration of southwestern ponderosa pine ecosystems: a broad perspective. Ecol Appl 12:1418–1433

Arno SF, Simmerman DG, Keane R (1985) Forest succession on four habitat types in western Montana. INT-GTR-177. USDA, Forest Service, Ogden, UT

Baker WL (1989) Effect of spatial heterogeneity on fire-interval distributions. Can J For Res 19:700–706

Baker WL (1992) Effects of settlement and fire suppression on landscape structure. Ecology 73:1879–1887

Baker WL (1993) Spatially heterogeneous multiscale response of landscapes to fire suppression. Oikos 66:66–71

Baker WL (1994) Restoration of landscape structure altered by fire suppression. Cons Biol 8:763–769

Baker WL, Ehle DS (2001) Uncertainty in surface fire history: the case of ponderosa pine forests in the western United States. Can J Forest Res 31:1205–1226

Baker WL, Veblen TT, Sherriff RL (2007) Fire, fuels, and restoration of ponderosa pine-Douglas-fir forests in the Rocky Mountains, USA. J Biogeogr 34:251–269

Belsky JA, Blumenthal DM (1997) Effects of livestock grazing on stand dynamics and soils in upland forests of the Interior West. Cons Biol 11(3):315–327

Bolsinger CL (1978) The extent of dwarf mistletoe in six principal softwoods in California, Oregon, and Washington, as determined from forest survey records. GTR-PSW-31. USDA, Forest Service, Berkeley, CA

Brown RT, Agee JK, Franklin JF (2004) Forest restoration and fire: principles in the context of place. Cons Biol 18(4):903–912

Chew J (1997) Simulating landscape patterns and processes at landscape scales. In: Proceedings of the 11th Annual Symposium on Geographic Information Systems. GIS World Publication, Fort Collins, CO

DeBano LF, Neary DG, Ffolliott PF (1998) Fire: its effect on soil and other ecosystem resources. John Wiley & Sons Inc, New York

Ehle DS, Baker WL (2003) Disturbance and stand dynamics in ponderosa pine forests in Rocky Mountain National Park. Ecol Monographs 73:543–566

Everett RL, Schellhaas R, Spurbeck D, Ohlson P, Keenum D, Anderson T (1997) Structure of northern spotted owl nest stands and their historical conditions on the eastern slope of the Pacific Northwest Cascades, USA. Forest Ecol Manage 94:1–14

Everett RL, Schellhaas R, Keenum D [and others] (2000) Fire history in the ponderosa pine/Douglas-fir forests on the east slope of the Washington Cascades. Forest Ecol Manage 129:207–225

Eyre FH (1980) Forest cover types of the United States and Canada. Soc. American Foresters, Washington, DC

Fulé PZ, Crouse JE, Heinlein TA, [and others] (2003) Mixed severity fire in a high elevation forest of Grand Canyon, Arizona, USA. Landscape Ecol 18:465–486

Hann WJ, Jones JL, Karl MG, [and others] (1997) Landscape dynamics of the basin. PNW-GTR-405, USDA, Forest Service, Portland, OR

Hessburg PF, Smith BG, Kreiter SD [and others] (1999a) Historical and current forest and range landscapes in the interior Columbia River Basin and portions of the Klamath and Great Basins: Part I: Linking vegetation patterns and landscape vulnerability to potential insect and pathogen disturbances. PNW-GTR-458. USDA, Forest Service, Portland, OR

Hessburg PF, Smith BG, Salter RB (1999b) Detecting change in forest spatial patterns from reference conditions. Ecol Appl 9(4):1232–1252

Hessburg PF, Smith BG, Salter RB (1999c) Using natural variation estimates to detect ecologically important change in forest spatial patterns: a case study of the eastern Washington Cascades. PNW-RP-514. USDA, Forest Service, Portland, OR

Hessburg PF, Smith BG, Kreiter SD [and others] (2000a) Classifying plant series-level forest potential vegetation types: methods for subbasins sampled in the mid-scale assessment of the Interior Columbia Basin. PNW-RP-524. USDA, Forest Service, Portland, OR

Hessburg PF, Salter RB, Richmond MB, [and others] (2000b) Ecological Subregions of the Interior Columbia Basin, USA. Appl Vegt Sci 3(2):163–180

Hessburg PF, Smith BG, Salter RB, [and others] (2000c) Recent changes (1930s–1990s) in spatial patterns of Interior Northwest forests, USA. For Ecol Manage 136:53–83

Hessburg PF, Agee JK (2003) An environmental narrative of Inland Northwest US forests, 1800–2000. Forest Ecol Manage 178:23–59

Hessburg PF, Reynolds KM, Salter RB, Richmond MB (2004) Using a decision support system to estimate departures of present forest landscape patterns from historical conditions: An example from the Inland Northwest Region of the United States. In: AH Perera, LJ Buse, MG Weber (ed) Emulating natural forest landscape disturbances: concepts and applications, ch. 13. Columbia University Press, New York, NY, USA, pp 158–175

Hessburg PF, Agee JK, Franklin JF (2005) Dry mixed conifer forests and wildland fires of the Inland Northwest: contrasting the landscape ecology of the pre-settlement and modern eras. Forest Ecol Manage 211:117–139

Heyerdahl E, Brubaker LB, Agee JK (2001) Factors controlling spatial variation in historical fire regimes: a multi-scale example from the interior West, USA. Ecology 82:660–678

Heyerdahl E, Brubaker LB, Agee JK (2002) Annual and decadal climate forcing of historical fire regimes in the interior Pacific Northwest, USA. Holocene 12(5):597–608

Huff MH, Ottmar RD, Lehmkuhl JF, [and others] (1995) Historical and current forest landscapes of eastern Oregon and Washington. Part II: potential fire behavior and smoke production. PNW-GTR-355. USDA, Forest Service, Portland, OR

Hunter ML (1990) Wildlife, forests, and forestry: principles of managing forests for biodiversity. Prentice Hall, Englewood Cliffs, NJ

Hunter ML (1993) Natural fire regimes as spatial models for managing boreal forests. Biol Cons 65:115–120

Hunter ML, Jacobsen GL Jr, Webb T (1988) Paleoecology and the coarse filter approach to maintaining biological diversity. Cons Biol 2:375–385

Johnson EA, Miyanishi K (2001) Forest fires: Behavior and ecological effects. Academic Press, San Diego, CA

Keane RE, Ryan K, Finney M (1998) Simulating the consequences of fire and climate regimes on a complex landscape in Glacier National Park, USA. Tall Timbers 20:310–324

Keane RE, Morgan P, White JD, (1999) Temporal pattern of ecosystem processes on simulated landscapes of Glacier National Park, USA. Landscape Ecol 14(3):311–329

Keane RE, Parsons R, Hessburg PF (2002) Estimating historical range and variation of landscape patch dynamics: limitations of the simulation approach. Ecol Modeling 151:29–49

Küchler AW (1964) Potential natural vegetation of the conterminous United States (manual and map.) Special Pub. 36. American Geographical Society, New York

Küchler AW (1975) Potential natural vegetation of the conterminous United States, 2nd edn Map 1:3,168,000. American Geographical Society, New York

Kurz WA, Beukema SJ, Klenner W, [and others] (2000) TELSA: the tool for exploratory landscape scenario analyses. Comp Electr Agric 27(1–3):227–242

Landres PB, Morgan P, Swanson FJ (1999) Overview of the use of natural variability concepts in managing ecological systems. Ecol Appl 9:1179–1188

Langston N (1995) Forest dreams, forest nightmares: the paradox of old growth in the Inland Northwest. University of Washington Press, Seattle

Lillybridge TR, Kovalchik BL, Williams CK, Smith BG (1995) Field guide for forested plant associations of the Wenatchee National Forest. PNW-GTR-359. USDA, Forest Service, Portland, OR

Minnich RA, Barbour MG, Burk JH, [and others] (2000) Californian mixed-conifer forests under unmanaged fire regimes in the Sierra San Pedro Mártir, Baja California, Mexico. J. Biogeogr 27:105–129

Moeur M, Stage AR (1995) Most similar neighbor: an improved sampling inference procedure for natural resources planning. Forest Sci 41(2):337–359

O'Hara KL, Latham PA, Hessburg PF, [and others] (1996) A structural classification for Inland Northwest vegetation. West J Appl Forest 11:97–102

Oliver CD, Larson BC (1996) Forest stand dynamics-update edition. John Wiley & Sons, New York

Robbins WG (1999) Landscape and environment: ecological change in the Intermontane Northwest. In: Boyd R (ed) Indians, fire, and the land in the Pacific Northwest. Oregon State University Press, Corvallis, OR

Rollins MG, Morgan P, Swetnam TW (2002) Landscape-scale controls over 20th century fire occurrence in two large Rocky Mountain (USA) wilderness areas. Landscape Ecol 17:539–557

Schoennagel T, Veblen TT, Romme WH (2004) The interaction of fire, fuels, and climate across Rocky Mountain forests. Bioscience 54(7):661–676

Seaber PR, Kapinos PF, Knapp GL (1987) Hydrologic unit maps. Water-Supply Paper 2294. USGS, Washington, DC

Shinneman DJ, Baker WL (1997) Non-equilibrium dynamics between catastrophic disturbances and old growth forests in ponderosa pine landscapes of the Black Hills. Cons Biol 11(6):1276–1288

SNEP (1996) Status of the Sierra Nevada. Assessments and scientific basis for management options. Wildland Resources Center Report No. 37. University of California, Davis

Spies TA (1998) Forest structure: a key to the ecosystem. Northwest Sci 72(2):34–39

Steele R, Geier-Hayes K (1989) The Douglas-fir/ninebark habitat type in central Idaho: Succession and management. INT-GTR-252. USDA, Forest Service, Ogden, UT

Stephens SL, Skinner CN, Gill SJ (2003) Dendrochronology-based fire history of Jeffrey pine-mixed conifer forests in the Sierra San Pedro Martir, Mexico. Can J For Res 33:1090–1101

Swetnam TW, Baisan CH (1996) Historical fire regime patterns in the southwestern United States since AD 1700. RM-GTR-286. USDA, Forest Service, Fort Collins, CO

Thompson ID, Harestad AS (2004) The ecological and genetic basis for emulating natural disturbance in forest management., In: Perera AH, Buse LJ, Weber MG (eds) Emulating natural forest landscape disturbances: concepts and applications, Columbia University Press, New York, NY, USA, chap 3. pp 29–42

Thornton PE, Running SW, White MA (1997) Generating surfaces of daily meteorological variables over large regions of complex terrain. J Hydrol 190:214–251

US Government (2003) Healthy Forests Restoration Act of 2003. 108th Congress, House Report 108–386:1–48

Weaver H (1943) Fire as an ecological and silvicultural factor in the ponderosa pine region of the Pacific slope. J For 41(1):7–15

Weaver H (1959) Ecological changes in the ponderosa pine forest of the Warm Springs Indian Reservation in Oregon. J For 57:15–20

Weaver H (1961) Ecological changes in the ponderosa pine forest of Cedar Valley in southern Washington. Ecology 42:416–420

White AS (1985) Presettlement regeneration patterns in a southwestern ponderosa pine stand. Ecology 66: 589–594

Whitlock C, Knox MA (2002) Prehistoric Burning in the Pacific Northwest. In: Vale TR (ed) Fire, native peoples, and the natural landscape. Island Press, Washington, DC

Whitlock C, Shafer SH, Marlon J (2003) The role of climate and vegetation change in shaping past and future fire regimes in the northwestern US, and the implications for ecosystem management. For Ecol Manage 178:5–21

Williams GD, Babcock WA (1983) The Yakima Indian Nation forest heritage: A history of forest management on the Yakima Indian Reservation, Washington, (for the 1983–1992 Forest Management Plan). Heritage Research Center, Contract No. POOC14207191, Missoula, MT

Wright CS, Agee JK (2004) Fire and vegetation history in the eastern Cascade Mountains, Washington. Ecol Appl 14:443–459