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Research article

Historical range of variability in eastern Cascades forests, Washington, USA

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Abstract

The historical range of variability (HRV) has been suggested as a coarse filter approach to maintain ecosystem sustainability and resiliency. The historical range of variability in forest age structure for the central eastern Cascade Range in Washington State, USA was developed from historical fire return intervals and the manner in which fire acted as both cyclic and stochastic processes. The proportions of seven forest structural stages calculated through these processes were applied to the area of each forest series within the central eastern Cascades landscape. Early successional forest stages were more common in high elevation forest than low elevation forest. The historical proportion of old growth and late successional forest varied from 38 to 63 percent of the forested landscape. These process-based estimates are consistent with those developed from forest structural information. HRV is a valuable planning tool for ecosystem conservation purposes, but must be applied to real landscapes with consideration of both temporal and spatial scale.

Introduction

The concept of ranges of variability in forest structural stages has been suggested as a framework for coarse filter conservation strategies (Landres et al. 1999). If it is possible to produce or mimic the historical ranges in stand structures by forest type on current and future landscapes, then much of the habitat for native flora and fauna should be recreated and maintained, assuming that past changes have not been so severe as to preclude restoration. Ecosystem resiliency may be dependent on maintaining critical types and ranges of natural variation in resource systems (Holling and Meffe 1996). Fine-filter strategies, such as individual species plans or snag retention, will still be needed, but most species and ecosystem elements should remain viable (Haufler et al. 1996).

Development of historical ranges of variability has included Delphi techniques (Hann et al. 1994), space-for-time substitution (Hessburg et al. 1999), and disturbance-based reconstructions (Cissel et al. 1999). Each of these techniques has strengths and weaknesses: the expert opinion of Delphi approaches can maximize limited data and utilize professional experience, but validity of estimates is unknown. Space-for-time substitution can utilize current spatial pattern in similar biophysical environments to develop a cross section of temporal variation at a site, but it assumes that modern temporal change has not been so significant as to negate a space-for time substitution (Hessburg et al. 1999). The strength of disturbance regimes to develop the historical range of variability is that fairly precise patterns can be reconstructed, but usually at a very local scale, so that inferences about broader landscape pattern are imprecise (Hessburg et al. 1999).

In this paper, the disturbance regime method is used to produce estimates of the historical ranges of variability for major forest types of the central eastern Cascade Range of Washington State, USA (Figure 1). Implications for ecosystem management are drawn from the results.

The approach to historical range of variability

Forests are dynamic systems, and within a forest ecosystem, the only constant is change. For forest trees, change occurs through tree growth and death, and for long-lived Pacific Northwest forest trees (400-800 yrs; Franklin and Dyrness 1973), natural disturbance was a major factor in terminating the life of trees. There are a number of natural disturbance factors, including insects, wind, disease, and fire, but it is generally recognized that fire was probably the most important landscape disturbance in the eastern Cascades. The process of fire created variability in forest pattern, and it clearly varied in frequency and intensity by forest type (Agee 1994). The process of fire also varied by fire regime (Agee 1998), and to understand the reconstruction of ranges of variability, some discussion of how fire differentially affected the distribution of stand ages is necessary. Three fire regimes are defined: low-severity, mixed-severity, and high-severity. Low-severity fire regimes had frequent but low-intensity fire; high-severity fire regimes had infrequent fire but usually high-intensity fire; and mixed-severity fire regimes had intermediate frequencies and a mix of low- moderate-, and high-severity patches created by fire. Two major types of assumptions are used to produce estimates of the distribution of historical stand ages or structures: (1) the processes are cyclic, stochastic, or a mix of the two, and (2) that quasi-equilibrium landscapes existed at some spatio-temporal scale (Frelich 2002).

Cyclic and stochastic properties of disturbance

Any forest stand has a probability that a disturbance will enter and kill the trees in the stand. The nature of the probabilistic process can either be *cyclic* or *stochastic*, independent of the actual probability of disturbance (K. McKelvey, USDA Forest Service, Missoula, MT, pers. comm., Agee 1999). Consider a coin with heads (H) and tails (T) as the only possible outcomes. If turned alternatively from side to side, it would create a pattern of HTHTHT etc. The probability, p, would be 0.5 for a head or a tail. This is a cyclic process, as it is very regular and predictable. Consider the distribution of forest stand ages as a cyclic process. The even-aged, area-regulated managed forest is a prime example of a cyclic system (assuming that natural disturbances are eliminated). The probability of age class X moving to age class X+1 is close to one (p = 1.0), and the probability of being "recycled" to age 0 is close to zero (p = 0), until the rotation age is reached, at which time the stand is cut and it moves to age class 0 with p = 1. Forest stands operating under a cyclic process will have a rectangular age class distribution, truncated at the rotation age (R). The average stand age is R/2, and there are no stands older than R. Historical forests in low-severity fire regimes likely mimicked a cyclic process. Bark beetles would typically kill an old growth patch, which would be decomposed by subsequent frequent fires, and into which young trees would successfully regenerate (Agee 1993). Once through the regeneration stage, frequent fires reduced fuels and allowed a stable patch structure to move forward over time into old growth, while adjacent older patches would be similarly recycled to a young patch. Old patches would "wink out" on the landscape and be replaced by young patches, a cyclic process at the patch level producing an equilibrium age class distribution at the forest level.

If the same coin were flipped in the air instead of turned from side to side, the probability would remain 0.5 for a head or tail, but the pattern might be HHTTH, so that tosses might produce runs of heads or tails. This is a stochastic process, even though the probability of head or tail is exactly the same as the cyclic process. Boreal forests are classic examples of natural forests regulated by fire acting in a stochastic manner (Johnson and Van Wagner 1985). The probability of any stand being burned in a given year (p) is low, generally below 0.05. The probability of a stand of age X moving to age X+1 is then 1-p. If this process is carried out for a long time, with flammability constant over age, then a negative exponential distribution will result. The frequency of any age class x is

$$f(x) = pe^{-px}$$

The average stand age is 1/p, or C, and this is commonly called the fire cycle. Roughly 1/3 of the stands are older than the average stand age, and there is no maximum age for a stand, in contrast to the distribution created by cyclic processes. As the fire cycle

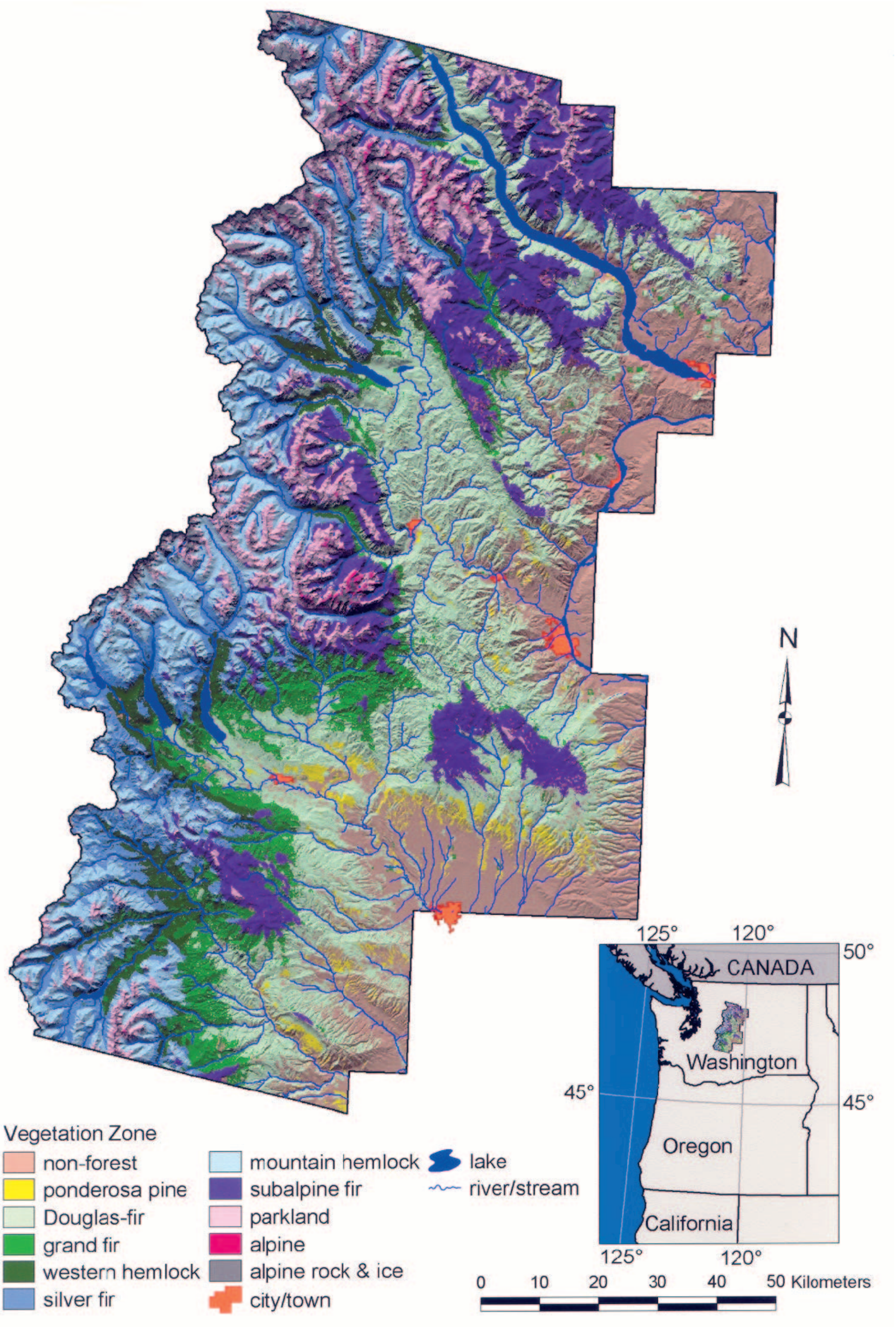

Figure 1. Major forest zones within the study area in the central eastern Cascades of Washington, USA. The western edge of the area is the crest of the Cascade Range, and the eastern boundary is parallel to the Columbia River.

changes by forest type, proportions of the landscape across various age classes will also change. For example, if the fire cycle is 100 yrs, almost 18% of the landscape will be in the 0-20 yr age class, with less than 17% older than 200 yrs. A fire cycle of 300 yrs will have slightly over 6% in the 0-20 yr age class, but over 55% older than 200 yrs. Of course, these older stands are likely to be affected by disease or insects, but this disturbance is usually at a much finer grain than the landscape effects of fire.

Equilibrium or non-equilibrium landscapes

If a given cyclic or stochastic process is projected over time, an equilibrium landscape is eventually produced. The shape of the age-class distribution will remain constant over time, although the shape will differ between the cyclic and stochastic models. While no individual stand is in equilibrium, the distribution of stand ages that make up the landscape is stable. However, if the probabilities of disturbance change over time, then a non-equilibrium state is introduced which may "ripple" through the age class distribution as a "blip", or if the probabilities of disturbance are continually changing, there may be no predictable range of variability for any age class or the age class distribution as a whole (Agee and Huff 1986).

Equilibrium in fire-affected landscapes is very much a function of scale: as scale decreases (in a cartographic sense), the total area becomes larger, more fires will occur, and the average fire size as a proportion of the total landscape declines. As this occurs, the assumptions necessary to apply a stochastic model such as the negative exponential become more reasonable, and quasi-equilibrium landscape conditions are therefore more plausible (e.g., Frelich 2002). What is an appropriate scale? The scale must be such that fire occurrence is regular rather than episodic, and does not burn "large" areas of the landscape when it occurs. This can require very large areas. Criteria for minimum dynamic area (Pickett and Thompson 1978) depend on the scale of processes operating on the landscape. Frelich and Lorimer (1991), in Michigan, suggested that no single disturbance should exceed 20 percent of the total area over a 250 year period. Johnson (1992), in boreal forests, suggested that the study area be at least twice the size of the maximum disturbance, but Frelich (2002) cautions that there is really no maximum disturbance size: a rare, but extremely large, disturbance is always possible.

The Yellowstone landscape (almost 1 million ha) is a good example of a non-equilibrium landscape. It is a broad subalpine plateau with few substantial natural firebreaks that rarely burns, but much of it burned in the early 1700s (Romme 1982). The forest age classes created by those early fires created a very large age class that moved as a "wave" through the age class distribution over time, so that much of the park's forest in the 1980's was old-growth, with lodgepole pine (*Pinus contorta*) being replaced by subalpine fir (*Abies lasiocarpa*) on many sites. In 1988, the large fires that burned across the national park killed much of the old-growth age class, as well as stands of younger ages. About half the park forest is now (2003) in the 15-year old age class, which may move as a similar age class "wave" in the future or be broken up by other non-equilibrium fires. For the past 300 years, and now for centuries to come, forests of the Yellowstone plateau have not and will not possess any equilibrium age class structure, due to "top-down" climatic influences (Lertzman and Fall 1998) that overwhelm "bottom-up" controls over fire such as fuels, slope, and aspect. If large subalpine forests of the Rockies and other western North America areas are considered, fire may well be more an equilibrium-maintaining process at that scale, particularly if landforms are more highly dissected (the "bottom-up" influences of Lertzman and Fall (1998)) so that individual fires cannot burn large proportions of the landscape in any year. For the purposes of the high elevation eastern Cascades, with highly-dissected terrain, an equilibrium assumption may be acceptable at a basin level (100,000-200,000 ha), as there is no evidence that fires of the scale of Yellowstone in the 1700s and in 1988 have burned there, even during drought periods. However, within the 20^{th} century a number of fires in the 20,000 ha range have burned, so at the subbasin scale (10,000-20,000 ha) the equilibrium assumption probably does not hold.

The application of a concept like historical range of variability implies that the forest landscape possesses at least quasi-equilibrium properties. If it were not, then we could substitute a range of 0-100% in each structural stage of each forest type and be satisfied that have encompassed the possible ranges of all non-equilibrium landscapes. Ecological theory today is rife with non-equilibrium evidence (Baker 1989; Lesica 1996; Gardner et al. 1999), from which

Table 1. Environment along a gradient from west (Snoqualmie Pass) to east (Ellensburg) through the center of the eastern Cascades, Washington, USA.

Station	Latitude	Longitude	Elevation	Mean Maximum Temperature	Mean Minimum Temperature	Mean Annual Precipitation	Mean Annual Snowfall
	Degrees and Minutes		m	°C	°C	cm	cm
Snoqualmie Pass	47 25	121 25	915	10.5	0.7	266	1119
Cle Elum	47 11	120 57	575	14.6	1.6	57	205
Ellensburg	46 58	120 33	448	15.6	1.7	23	71

one might infer that equilibrium landscapes neither exist nor are a useful target for management. This is partially the result of backlash against almost a century of ecological equilibrium theory that postulated, with little evidence, that convergence of a wide variety of regional vegetation types would occur, that later successional communities were always more stable and diverse, and that natural disturbance was rare (Clements 1935; Odum 1969). These postulates have now been discarded, and the notion of change and surprise is the new ecological paradigm, built into theory and practice (such as adaptive management (Walters 1986)). These dynamics and effects are also known to be dependent on temporal and spatial scales (Wiens 1989). Of particular relevance in this study is the stability of age class structure, characteristic of an equilibrium landscape, which can occur but is highly dependent on the scale of observation (Shugart 1984; Frelich 2002). No point is ever in equilibrium, but a series of stands may approach an equilibrium structure through cyclic or stochastic processes. A major caveat to using equilibrium landscape models as models for future management are the climatic changes associated with either past environments (Little Ice Age) or current understanding of global change scenarios. Any reconstructions using historical ranges of variability must be interpreted in the context of a changing environment (Romme and Turner 1991).

The environment of the eastern Cascades

The central eastern Cascade Mountains are located between 47.4 and 48.4 degrees North latitude and 119.9 to 121.5 degrees West longitude in Washington State, USA. They form a barrier to the major storm tracks that move from the Pacific Coast inland, such that precipitation is maximized at the crest of the Cascades, the west edge of the study area, and declines rapidly to the east through the study area (Table 1). Total annual precipitation may exceed 380 cm at the highest elevations along the crest (Hessburg et al. 2000a), but weather stations represented in Table 1 show less total precipitation. Snoqualmie Pass is at the extreme west of the study area, Cle Elum is centrally located, and Ellensburg is at the eastern edge. Precipitation is concentrated in winter months (75 percent from November-April) and falls mainly as snow. The eastern Cascades of Washington have the most maritime climate within the interior Columbia Basin because of the proximity to Pacific coast air masses (Hessburg et al. 2000a).

Landforms represent a very complex geologic history dominated by volcanic processes. The southern portion of the study area and the eastern boundary are underlain by Columbia Plateau basalts that are well represented further east. Sandstones, metamorphic rocks, and granites underly the central portion of the study area, with inclusions of serpentinite (Alt and Hyndman 1984). The northern portion of the study area is underlain by gneiss and granite. Many of the broad valleys were shaped by glaciation that began to retreat in the early Holocene.

The forest types of the eastern cascades and their age distribution

A brief summary of the species composition and dynamics of the major forest types is presented here to provide context for the approach used to create the structural variability described later in the paper. The forests of the eastern Cascades reflect the “top-down” climatic controls of decreasing precipitation and increasing temperature from west to east, and local “bottom-up” controls of landform such as cold air drainage and effects of aspect and slope. Both top-down and bottom-up processes have influenced forest types and their associated fire regimes.

Table 2. Fire history in the major vegetation types of the eastern Cascades. Studies from related vegetation types in other areas were used as appropriate.

Fire Return Interval (years)	Method[1]	Location	Source
Pinus ponderosa series			
7-20	CFI (16)	E. Oregon	Bork (1985)
11-16	P	E. Oregon	Weaver (1959)
3-36	P	E. Oregon	Soeriaatmadja (1966)
Pseudotsuga menziesii series			
7-11	CFI (20)	E. Washington	Wischnofske and Anderson (1983)
10	P	Blue Mtns	Hall (1976)
10-24	P	E. Washington	Finch (1984)
14	CFI (40)	E. Washington	Finch (1984)
8-18	P	E. Washington	Agee (unpublished data)
18	CFI (3)	E. Washington	Wright (1996)
6-8	CFI (450)	E. Washington	Everett et al. (2000)
Abies grandis series			
47	P	E. Oregon	Weaver (1959)
33-100	CFI (30)	E. Washington	Wischnofske and Anderson (1983)
17[2]	P	Montana	Arno (1976)
100-200[3]	–	Montana	Antos and Habeck (1981)
18	CFI (3)	E. Washington	Wright (1996)
Abies lasiocarpa series			
25-75[2]	–	Montana	Barrett et al. (1991)
109-137	NFR	C. Washington	Agee et al. (1990)
140-340[3]	–	Montana	Barrett et al. (1991)
250	–	E. Washington	Fahnestock (1976)
50-300[4]	CFI	Northern Rockies	Arno (1980)

[1]P = point or individual tree, CFI = composite fire interval, with size of area used (ha) in parentheses, NFR = natural fire rotation; [2]intermediate intensity fire return interval; [3]stand replacement fire return interval; [4]stands dominated by whitebark pine; synthesis of several studies with variable methods of compositing the fire return intervals

There is substantial evidence that all of the disturbance concepts described in section 2 fit one or another of the forest types of the central eastern Cascade area: cyclic, stochastic, equilibrium, and non-equilibrium systems are present. The major forest plant association groups (PAGs – group of closely related potential vegetation (Daubenmire 1968); two or more PAGs with the same potential overstory dominant are collectively know as a forest series) found from low to high elevation had a range of structural stages that were controlled by varying disturbance frequencies and intensities, as modified by climate and landform. Forest fires (Table 2), insects, and to some extent disease were the "natural managers" of the landscape prior to modern forestry. Native Americans were likely the source of many fires (e.g., Vale 2002), especially in the drier forest types, but lightning ignitions were common, too, and without suppression, had the capability of burning across the landscape for months (Agee 1993).

The Ponderosa pine and Douglas-fir PAGs

Most of the plant associations in the Ponderosa pine (*Pinus ponderosa*) and Douglas-fir (*Pseudotsuga menziesii*) series had frequent fire return intervals (Table 2), and probably the most frequent fire activity for any forest type in the Pacific Northwest (Agee 1994; Everett et al. 2000). Fire intensities appear to have been low where associated understory species were elk sedge (*Carex geyeri*), long-stolon sedge (*C. pensylvanica*), pinegrass (*Calamagrostis rubescens*), or bearberry (*Arctostaphylos uva-ursi*). Longer fire return intervals than shown in Table 2 and higher fire intensities have been found in east Cascades forests when understory dominants are snowberry (*Symphoricarpos* spp.), ninebark (*Physocarpus malvaceus*), and huckleberry (*Vaccinium* spp.) (Agee 1994; Williams et al. 1990).

Frequent low-intensity fires kept these forests open and park-like (Figure 2A), typically with wide-

Figure 2. A. Ponderosa pine was a major historical dominant in the Ponderosa pine, Douglas-fir and Dry Grand Fir PAGs. B. Douglas-fir and grand fir share dominance with ponderosa pine in the Dry Grand Fir PAG. Harvest of the large ponderosa pines in the foreground has been a common practice. C. In the Wet Grand Fir PAG, Douglas-fir, grand fir, lodgepole pine and western larch (the deciduous conifer in the foreground) were potential dominants. D. In the subalpine PAGs, continuous forest grades into parkland environments where tree clumps share landscape dominance with low shrub and herbaceous meadows.

spaced, large clusters of trees and a carpet of low shrub/herbaceous vegetation, a classic low-severity fire regime (Agee 1993). Ponderosa pine was the dominant tree. Between fires, pine or both pine and Douglas-fir regeneration would establish under the mature tree canopy but grow slowly, and would almost always be killed as it would be less than 1 m tall when the next fire passed through the area. Fire would selectively favor ponderosa pine, as it develops thicker bark faster than Douglas-fir and grows faster on these sites. Occasionally a Douglas-fir would be missed by a fire or two and this was responsible for the isolated, very large Douglas-fir trees and stumps seen in this forest type today. As a stand developed, fire would thin the trees such that low tree density (70-100 trees ha^{-1}) was characteristic of the old growth stands (Harrod et al. 1999). Little tree understory or coarse woody debris existed in these stands. Almost all of the shrubs and herbs are sprouters or rhizomatous, so they were very resilient in the face of frequent topkill by these low-intensity fires.

When a senescent group of pines was killed by bark beetles, subsequent fires would burn up the snags and logs and create a new gap for pine regeneration to survive. The heat of these fires, while consuming the woody debris, retarded shrub and herb competition long enough for a new tree cohort to establish and perpetuate the clumped pattern of trees on the landscape. Both ponderosa pine and Douglas-fir would establish in these openings, but pine was favored by the fires. Coarse woody debris was also clustered on the landscape, being created as the older tree clumps were group-killed by bark beetles, and as one clump was recycled by fire, another would appear elsewhere on the landscape in another old patch of trees. Fire acted as a negative feedback mechanism for fire intensity: the more fire occurred, the less intense it could be due to lack of fuel energy (except in the beetle-killed clusters). These forests followed a cyclic pattern of disturbance with patches burning often and remaining stable in the presence of fire.

In this forest type, western spruce budworm activity (*Choristoneura occidentalis*) was largely absent because of a lack of host material to sustain the population. However, on sites where fire return intervals were longer than 15-20 years, Douglas-fir and/or grand fir were substantial components of the stands and spruce budworm activity was historically evident (Anderson et al. 1987). Defoliation of ponderosa pine by the pine butterfly (*Neophasia menapia*) occurred in 1893-95 in the Klickitat Valley, causing some pines to be killed by bark beetles and replaced with even-aged stands of pine (Weaver 1961), but this pattern appears to be relatively anomalous for the region.

Dry Grand Fir PAG

The drier plant associations in the Grand Fir (*Abies grandis*) series have fire return intervals (Table 2) very similar to those of the Douglas-fir PAG (Agee 1994; Wright 1996). Historical fire intensities were low for the most part, also similar to the Douglas-fir series. These slightly moister plant associations might have had slightly more patchy fire spread, or slightly longer fire return intervals, plus better growing sites for Douglas-fir and grand fir (Figure 2B).

Some of these sites appear to have been dominated by ponderosa pine, while other sites had at least codominance by Douglas-fir. Grand fir, the late successional species on these sites, was less commonly a codominant. These forests also appear to have been fairly open, parklike stands, with clusters of mature trees (probably clumped into pure species groups, similar to other mixed-conifer forests (Bonnicksen and Stone 1981; Thomas and Agee 1986)). Like the Ponderosa Pine and Douglas-fir PAGs, the Dry Grand fir PAG is also a low-severity fire regime (Agee 1993). Spruce budworm activity was historically episodic on such sites, affecting survival and growth of Douglas-fir and grand fir.

Wet Grand fir PAG

The Wet Grand Fir PAG includes cooler, moister sites on which grand fir is the climax species. Evers et al. (1997) define this type as the those plant associations with grand fir or grand fir/Engelmann spruce (*Picea engelmannii*) and understory dominants vine maple (*Acer circinatum*), vanillaleaf (*Achlys triphylla*), thimbleberry (*Rubus parviflorus*), and big huckleberry (*Vaccinium membranaceum*). It is typical of mid-elevations, fingering down into lower elevation perennial stream channels or cold air drainages. The Wet Grand Fir PAG can be differentiated from the drier types by the occurrence of lodgepole pine, western larch (*Larix occidentalis*), and western white pine (*Pinus monticola*), with ponderosa pine being uncommon and Engelmann spruce occasionally present on wetter sites (Figure 2C).

Fire tended to be less common on these sites (Table 2) than in the Dry Grand Fir PAG (Agee 1993; Agee 1994; Wright 1996), and these are commonly classified as mixed-severity fire regimes. Under normal conditions, fire may not spread well in this type, but under unusual fire weather, fires can be very high intensity, and the multi-layered forest structure that would develop in the absence of fire could result in crown fire behavior. At the same time, other stands would be thinned and others simply underburned, creating a complex mosaic of stand types within the Wet Grand Fir PAG. The wide range of regeneration environments resulted in ideal conditions for regeneration of most of the major species somewhere: lodgepole and western larch on high-severity stand replacement patches (Cobb 1988), Douglas-fir and grand fir on moderate-severity patches, and either grand fir or no regeneration in underburned areas where little overstory mortality occurred. The Wet Grand Fir PAG probably had the most host material for western spruce budworm outbreaks. However, sites where budworm outbreaks are most likely are areas with relatively warm and dry spring climates (Hessburg et al. 1994), less likely at higher elevations with cooler spring weather. Nevertheless, historical budworm activity was probably visible here because this PAG had the most Douglas-fir, grand fir, and Engelmann spruce host material.

Fire in this forest type tends to follow both cyclic and stochastic patterns, with assumptions of equilibrium conditions more tenuous. Stand replacement burning occurs and can be considered a stochastic process. Camp et al. (1997) identified stands in this type that acted as "fire refugia" in the past, and for this type 17.6% of the plots in the grand fir type were fire refugia with age defined as 140 years or greater. Using a property of the negative exponential distribution, the fire cycle is calculated as 75 years for this portion of the Wet Grand Fir type. However, the fire regime is a mix of stand replacement burns and underburns, so the structural stages are a combination of both cyclic and stochastic processes.

Table 3. Mechanics of developing the historical range of variability estimates for the central eastern Cascades of Washington, USA.

Step	Operation	Source of Information
1	Identify the Plant Association Group (PAG)	Lillybridge et al. (1995)
Steps 2-6 are within a PAG:		
2	Identify the range of fire return intervals	See Table 2 sources
3	Classify the fire process as stochastic or cyclic	References in Sections 4.1 − 4.4
4	Identify the range of site index	Lillybridge et al. (1995), see Table 4
5	Identify size classes from age for the range of sites	Schumacher (1930), Meyer (1938)
6	Calculate the proportion of landscape in each structure class as a range	Use steps 2-5, see Table 5
7	Identify area of each PAG in the study area	Unpublished data, T. Lillybridge, USDA Forest Service; see Figure 1 and Table 6, column 2
8	Calculate range of area in each PAG by structure class	See Table 6

Forested PAG's at higher elevation

The eastside forest types at higher elevation generally had long fire return intervals (Table 2) and high severity (stand replacement) fire regimes (Figure 2D). Often these types are pockets of forest in protected ridge areas, near valley bottoms, on north aspects, or near the Cascades crest (Figure 1), primarily in the *Abies lasiocarpa* or *Tsuga mertensiana* series, but also including the *Abies amabilis* series. Few fire history studies have been done in these areas, because they rely on area frequency techniques (cf. Agee 1993) and often occur over very limited areas of continuous forest in these types.

The fire return intervals for the higher elevation forest types are consistent with fire return intervals from similar forest types elsewhere (Agee 1994). Some local corroborating evidence was gathered as well. Maps of eastern Cascade forests in 1900 (Gannett 1902) show high elevation areas burned by stand replacement fire previous to 1900. These maps show fires of the previous 50 years (Agee et al. 1990). Areas between 1050-1800 m elevation were delineated on the map, and from the area 50 years or less in age, a "fire cycle" of 306 years was estimated using a negative exponential distribution (including all higher elevation forest types). Using a shorter record of 1924-36 fire statistics over a large eastside area (Cowlin et al. 1942), including much more area to the north (Entiat-Chelan-Okanogan), a fire return interval of 133 years was calculated using the same technique. The data from Camp et al. (1997) were used in a similar fashion. The proportion of "refugia" plots above 130-150 years of age for the subalpine fir type resulted in a fire cycle of 361 years in the Blewett Pass area.

Methods

The mechanics of developing the historical range of variability estimates are described below and summarized in Table 3. The drier forest types (Ponderosa Pine PAG, Douglas-fir PAGs, and Dry Grand Fir PAG) were assumed to have a uniform distribution of age classes. This cyclic equilibrium model has patterns of stand development that with high probability move stands from age class X to age class X+1, and eventually reaching senescence where bark beetles kill the group, "recycling" the stand to age 0. Stands were assumed to grow to age 400, although evidence suggests that bark beetles killed stands both younger and older at times. Although trees older than 400 years can be found in lower elevation forests, most trees do not exceed this age. Everett et al. (2000) could not extend fire history data back more than 300 years in this area, while Wright (1996) was able to extend a master tree-ring chronology to 425 years. Agee (2003) had complete age data for similar species composition stands in southern Oregon and found only 3% of trees that were older than 100 years were also older than 400 years, and only a single tree exceeded 413 years of age. These forest types were probably closest to true equilibrium landscapes in pre-settlement times, although age at senescence may have varied somewhat. A relatively stable age structure would have been maintained by frequent fire, with the oldest stands probably 350-450 years of age. This was modeled as a uniform distribution with equal area in each age class up to age 400 (5% in each 20-year age class).

In the remaining forest types, negative exponential models were applied in part or in whole to the fire return interval data to allocate proportions of land area to age classes. While one might argue whether or not these are equilibrium systems maintained by disturbance, equilibrium models tend to fit above some scale where the size of the average fire event is small in comparison to the total area under consideration (Agee 1993). Johnson and Gutsell (1994) estimate the fire event threshold at about 33% of the study area, but this seems quite high in relation to the assumptions of the negative exponential model. Based on 1900 type maps for the eastern Cascades (Gannett 1902), it appears that the largest fire event in the high elevation forest types is less than 10 percent of the study area, so negative exponential models appear to meet that criterion. This is well below the 20 percent criterion used by Frelich and Lorimer (1991).

In the Wet Grand Fir type, a mixed distribution of fire severities occurs, with some stand replacement burns and some underburning. In order to distribute age classes in this type, I assumed that 2/3 of the landscape in this type had stand replacement burning and followed a negative exponential age class distribution, while the other 1/3 of the landscape had a more cyclic age class distribution. In the other high-elevation forest types, negative exponential models were applied to the ranges of fire return intervals to produce landscape proportions by age class.

Disturbance created tremendous diversity in forest species composition and structure in eastern Cascade landscapes. Attempts to define the structural diversity of these landscapes is difficult due to different disturbance regimes and the possibilities of multiple pathway succession. The results are expressed here as a range of proportions of a forest type and the area within the central eastern Cascades historically expected in grass-forb, shrub-seedling (trees 0.1-8 cm diameter), sapling pole (8.1-20 cm), small tree (20.1-40 cm), medium tree (40.1-64 cm), large tree (> 64 cm) and late successional classes. In most cases the larger and late successional categories could not be separated, and were denoted as either "not present" in some of the drier forest types, or as some fixed percentage of the larger forest proportions that could be estimated. No attempt was made to estimate historical ranges of variability for the snowline communities where burns must have been historically quite patchy, and regeneration after disturbance was highly controlled by post-disturbance climate (Agee and Smith 1984; Little 1992).

The structural estimates were made using the proportions of age classes derived from fire history analyses into broader size classes defined by site productivity estimates. Plant associations were grouped and site index was estimated from the Wenatchee National Forest Plant Association Guide (Lillybridge et al. 1995). For the Ponderosa Pine, Douglas-fir, and Dry Grand Fir PAG's, the range of ponderosa pine site index (low and high) was used (Table 4). For the higher elevation PAG's, Douglas-fir site index was used (or estimated as closest fit). Site index is defined as the height of dominant trees in a stand at a fixed base age, such as 100 years, and can be used to predict growth and yield from a forest stand of any age by using a series of harmonic curves relating height to age. The site index can then be used in yield tables to estimate size and yield by age. From ponderosa pine and Douglas-fir yield tables (Schumacher 1930; Meyer 1938), for the range of site index recorded for each PAG, the age-size relationships by site index were used to determine at what ages a typical stand would move from one structural stage to another (e.g., sapling-pole to small tree). There were usually two ages derived for each structural class, representing the range of site potentials for that PAG. For each site class/fire return interval scenario in each PAG (from 2 to 4 scenarios, depending on the range of fire return interval and site index for that PAG, Table 4), the proportion of the landscape in each structural

Table 4. Assumptions used to create age class distributions by fire return interval and site class for each Plant Association Group for the central eastern Cascades, Washington, USA.

Plant Association Group	Fire Return Interval Range	Site Index[1]
All Ponderosa Pine	–[2]	PP 50-80
Douglas-fir Warm-Dry	–	PP 60-90
Douglas-fir Cool-Dry	–	PP 75-130
Grand Fir – Warm	–	PP 90-105
Grand Fir-Cool-Mesic	75[3]	PP 90-135
Western Hemlock	100-300[4]	DF 60-75
Pacific Silver Fir-Cool	150-400	DF 70-80
Pacific Silver Fir-Cold	200-400	DF 60
Subalpine Fir-Cold-Dry	100-200	DF 60-70
Subalpine fir-Cool-Moist	150-300	DF 60
Mountain Hemlock	300-500	DF 60

[1]Site Index for ponderosa pine is base age 100; for Douglas-fir, base age 50
[2]Fire return interval not needed for dry forest age classes – uniform distribution of age classes assumed (see text, Section 5)
[3]This PAG was modeled partly with a stand replacement fire regime (average age 75 years) and partly with a uniform distribution
[4]From here to bottom of table the negative exponential distribution is used to create age classes.

Table 5. Ranges of variability of structural classes by Plant Association Group (PAG). Each row contains the proportion of that type (0-1.0) in each structural stage historically present on the landscape of the central eastern Cascades, Washington, USA.

Plant Association Group	Grass-Forb	Shrub-Seed-ling	Sapling-Pole	Small Tree	Medium Tree	Large Tree	Late Successional
All Ponderosa Pine	.012-.025	.05-.10	.10-.137	.20-.213	.338-.426	.1-.3	Not Present
Douglas-fir Warm-Dry	.012-.025	.03-.075	.087-.125	.188-.275	.325-.35	.15-.35	Not Present
Douglas-fir Cool-Dry	.01-.012	.04-.05	.025-.113	.137-.2	.188-.325	.3-.6	Not Present
Grand Fir – Warm	.012	.025-.03	.076-.087	.163-.188	.2-.325	.35-.525	Not Present
Grand Fir-Cool-Mesic	.02-.045	.07-.125	.115-.215	.27-.295	.145-.18	.1-.16	.1-.16
Western Hemlock	.017-.095	.031-.235	.083-.212	.164-.294		.203-.698	
Pacific Silver Fir-Cool	.012-.064	.025-.117	.067-.192	.144-.284		.343-.750	
Pacific Silver Fir-Cold	.025-.049	.07-.132	.065-.114	.152-.256		.449-.688	
Subalpine Fir-Cold-Dry	.049-.095	.09-.235	.114-.192	.218-.294		.203-.523	
Subalpine fir-Cool-Moist	.033-.066	.092-.17	.083-.139	.205-.284		.342-.587	
Mountain Hemlock	.02-.033	.057-.092	.054-.083	.143-.205		.587-.726	

class was calculated by summing the proportions within the age classes expected to be in each size class. The yield tables were not designed to provide size-age equivalents for the larger size classes (medium and large trees and late-successional). Because the late successional category overlaps considerably with these other classes, the proportions calculated for some of the larger group of classes were left undifferentiated. Proportions were applied to the area of each forest type (unpublished data from T. Lillybridge, USDA Forest Service, Wenatchee, WA, USA) to develop ranges of area covered by each structural type in each forest series.

Results

The historical ranges of variability show a number of patterns across the forest types (Table 5-6). The grass-forb and shrub-seedling stages appear to be more confined in the drier types than in the cooler, moister, high-elevation types. This is due to the uniform distribution applied to the drier forests and the stability of older age classes, once established, in the presence of low intensity, frequent fire. In the drier types, the mid-seral stages appear to be prolonged. This is because the trees grow more slowly, and on the driest sites may never reach the "large" tree category (>64 cm). Multi-layered, late successional forest was assumed to be too rare to occur in the dry forest types, as even riparian zones commonly burned at intervals similar to the uplands (Olson 1999). In the Grand Fir – Cool-Mesic type, the proportion of the landscape was split equally between "large tree" and "late successional" because of the mixed model of age classes applied uniquely to this type.

There is a high proportion of each PAG in the "medium tree" to "late successional" categories, suggesting a once widespread distribution of mature to older growth forests in the eastern Cascades. The range across all forest types (Table 6) is 38 to 63 percent of the study area. The three types where these structural stages may have been more limited are where more frequent stand replacement fire was a common presence, generally at intervals of 100 years or less (the Grand Fir Cool-Mesic, Western Hemlock-Pacific Silver Fir Warm, and Subalpine Fir Cold-Dry PAGs), yet older forest would have commonly been juxtaposed with the disturbed areas.

Wide ranges of variation exist for the cooler, moister forest types because of the wide ranges of fire return intervals used. These might have been condensed somewhat by either assuming a narrower range of fire return intervals, or using a simple mean, or by further differentiating the PAGs to compartmentalize smaller ranges of variability. The difficulty with the former options is that they lump variability only for the sake of creating smaller ranges. The latter option is constrained by the lack of available fire history information at levels below the forest series (above the PAG), and that as the area considered shrinks, the scale issue so critical to using a negative exponential distribution becomes a barrier to using that distribution.

The range of proportions in any cell (Table 5) may be the range of two to four values based on site potential and assumed disturbance frequency. The cooler-moister types (Western Hemlock/Pacific Silver Fir/Subalpine fir/Mountain Hemlock) show a fair de-

Table 6. Historical ranges of variability (thousand ha) of plant association groups by structural stage in the eastern Cascades of Washington, USA.

Plant Association Group	Total Area	Grass Forb	Shrub-Seedling	Sapling-Pole	Small Tree	Medium Tree	Large Tree	Late Successional
	thousand ha							
Ponderosa Pine	51	0.6-1.3	2.6-5.1	5.1-7.0	10.2-10.7	17.2-21.7	5.1-15.3	n.a.
Douglas-fir Warm-Dry	206	2.5-5.2	6.2-15.5	17.9-25.8	38.7-56.6	67.0-72.1	30.9-72.1	n.a.
Douglas-fir Cool-Dry	57.5	0.6-0.7	2.3-2.9	1.4-6.5	7.9-11.5	10.8-18.6	17.2-34.5	n.a.
Grand Fir Warm	44.5	0.5	1.1-1.3	3.4-3.9	7.2-8.4	8.9-14.4	15.6-23.3	n.a.
Grand Fir Cool-Mesic	101	2.0-4.5	7.1-12.6	11.6-21.7	27.3-29.8	14.6-18.1	20.2-32.4	−
Western Hemlock	77	1.3-7.3	2.4-18.1	6.4-16.3	12.6-22.7		———15.6 to 53.7———	
Pacific Silver Fir Cool	64.5	0.8-4.1	1.6-7.5	4.3-12.3	9.3-18.3		———22.1 to 48.3———	
Pacific Silver Fir Cold	19.5	0.5-1.0	1.4-2.6	1.3-2.2	3.0-5.0		———8.8 to 13.4———	
Subalpine Fir Cold-Dry	85.5	4.2-8.1	7.7-20.1	11.9-16.4	18.6-25.1		———17.3 to 44.7———	
Subalpine fir Cool-Moist	25.5	0.8-1.7	2.3-4.3	2.1-3.5	5.2-7.2		———8.7 to 15.0———	
Mountain Hemlock	140.5	2.8-4.6	8.0-12.9	7.6-11.6	20.1-28.8		———82.4 to 102.0———	
Parkland	71.5							
TOTAL	944							

n.a. = not applicable

gree of variability in the "medium tree" to "late successional" categories. These were not separated as the available yield tables had no size-age transitions for these classes. The reason for the wide ranges were both variability in site index, and variability in disturbance interval. For example, the Western Hemlock-Pacific Silver Fir-Warm type had disturbance intervals from 100 to 300 years, and that alone creates a significant range of landscape proportions by age class. When the landscape proportions for each scenario are calculated and then the low and high end of the ranges are collated, a wide range of variability is evident, and various values in each row will not sum to 1 except by chance.

Discussion

The calculated historical ranges of variability by forest type could be interpreted as a tautology without supporting information verifying that reasonable assumptions were applied to the various forest types. There are at least two independent sources of data that evaluated structural variability in the same region of the eastern Cascades. Hessburg et al. (2000b) evaluated a somewhat larger area called the "northern Cascades" in a regional analysis of the Columbia Basin. Camp et al. (1997) evaluated a smaller area that is a subset of the central eastern Cascades. Although both studies used structure-based analyses, and have slightly different spatial and temporal scales, their results appear consistent with the process-based historical ranges shown in Table 5 and Table 6. The Hessburg study shows 11.6% of the forest in very early successional "stand initiation" structures in the 1930s, while this study shows a range of 6.3-15.0% in stages through seedling-sapling. Their older forest structures (old-forest, both single and multi-layered; understory reinitiation; and stem exclusion open canopy) totaled 41.2% of the landscape, compared to this study's range of 38.4-63.5% for the medium tree and larger/older stages. Their figure at the lower end of the range represents a point in time just after some very large regional fires during droughts of the 1920s. Because of the larger temporal scale of the fire history data in this study, the HRV range should be broader and does encompass the estimate from the Hessburg et al. study.

The Camp et al. (1997) analysis indicates that 12% of the forest was in late-successional and old-growth patches, and that much of it was found in "refugia" located on north aspects, valley bottoms, and drainage headwalls. While their study accurately depicts their entire 47,000 ha area, less than half of the area is high elevation forest where late-successional forest structure would be expected. When only the high elevation portion of their study is considered, the refugia total 28.7% of the area of grand fir and subalpine fir forest. This portion of their study area is also the most easterly and driest subalpine forest type within the larger central eastern Cascades (the large isolated block of subalpine fir forest in the southeastern portion of Figure 1). If the structural stages for the dry-cold subalpine fir type are used for comparison (Table

5), most typical of the high elevation forest in the Camp et al. study, the historical range of variation in large, old forest of this type is 20.3-52.3%, a wide range that nevertheless encompasses their refugia proportion of 28.7%.

This HRV-based study relaxed some of the more stringent assumptions of equilibrium fire regimes by allowing fire return interval to vary, particularly for the fire regimes of higher severity. This allowed the range of quasi-equilibrium conditions of structural stages to be wider than if site quality alone were the only variable within a forest type, and produced a wider range of area in any structural class. These are fairly broad ranges that could have been reduced if more site-specific information on fire history were available at a more local scale. Process-based reconstructions appear to be compatible with structure-based reconstructions of historical ranges of variability, for after all, process and pattern are closely linked (Wiens 1989; Wiens et al. 2002). The differences between process- and structure-based approaches are not as significant as one might assume, a finding applicable to many forest types (Stephenson 1999). Process creates pattern, but pattern itself is indicative of process. Notions of quasi-equilibrium (cf. Frelich 2002) cyclic and stochastic age class distributions in these forest types appear to fit real forest structures.

The HRV results have substantial utility in landscape planning, but must be applied with caution. Within the study area, much of the area is designated as national forest. Some of the national forest is legislatively designated wilderness, particularly higher elevation areas near the crest, and all of it is covered by the Northwest Forest Plan, an administratively designated conservation plan for Federal lands. Allocations outside of wilderness include late successional reserves (intent to create older, multi-layered forest), riparian reserves (unmanaged corridors along streams), and matrix lands (areas that are not covered by one of the other categories). The results here suggest that for late successional reserves, an objective to create large, homogeneous blocks of late successional forest would neither be within the range of natural variability nor even possible, given the past and future presence of wildfire. Well less than one-third of the landscape was in late-successional structure, although at lower elevation there were a lot of medium to large trees in more simplified single-canopy structures. For higher elevation areas, the late successional patches are likely to "migrate" around the landscape, as one patch is burned by high-severity fire but elsewhere another is developing. In lower elevation areas, managing for larger trees will require more active fuels management to protect the large tree component from currently unusually intense wildfire. Major changes over the twentieth century in the dry forests include increases in shade-tolerant species, loss of old forest patches and older, larger trees in general, increases in intermediate-sized and multi-layered forest structure, and increases in potential severe fire behavior (Hessburg et al. 2000b; Agee 2002). Future management oriented towards biodiversity concerns should focus on moving these ecosystems back towards the historical range of variability. The HRV estimates can be useful as area targets but are not informative about patch size and pattern. These are available from more structurally-based approaches that were developed from shorter time series analyses (Hessburg et al. 2000b).

Private lands, a majority owned by industrial forest companies, are intermixed and adjacent to the Federal lands. Some of these companies have entered into habitat conservation plans (HCPs) under the Federal Endangered Species Act. The HCP is a long-term (typically 50-year) commitment by the landowner to develop certain forest structures and amounts to provide habitat for threatened, endangered, and other wildlife species. In return, the landowner is exempt from prosecution for incidental take (harassment or kill) of the species covered in the plan. Several of the larger landowners in the study area have completed or considered HCPs, and the HRV concept can be useful in defining amounts of target structures for the landowner. Depending on the landscape context of the private and Federal lands, more comprehensive long-term habitat creation and maintenance is possible, and progress towards these targets is easily monitored.

Ecosystem planning using HRV must recognize the importance of scale and avoid focusing on individual structural stages. While the scale of the study area appears to be sufficient to produce quasi-equilibrium age class analyses, more local scales might not encompass enough land area. One nearby late successional reserve, for example, is about 6000 ha with roughly 2000 ha in subalpine fir, a high-severity fire regime. At any one time in the past, the entire area could have burned in a single fire, so this scale is inappropriate for planning because potential disturbance size exceeds the total area. In the Coast Range of Oregon, Wimberly et al. (1999) simulated historical variability in old forest amounts. The historical old-growth percentages ranged from 25-75% at the province scale (2.2 million ha), but varied from 0-100% at the watershed scale (40,000 ha). In the higher elevation eastside Cascade forests, where fires were infrequent but often large, similar scale issues would apply. In the lower elevation forests, a much more local scale (1,000 ha) would be sufficient to evaluate stands, as that scale might include as many as 10,000 patches of pine and Douglas-fir forest.

Using the high end of the early successional "ranges" as a template for management, rather than the ranges of all structural stages, will not create appropriate ranges of structural variability, as it will result over time in a dearth of older age classes. In one real example from a ponderosa pine forest, managers assumed, with little real data, that natural ranges of variability for grass-forb and seedling-sapling stages were up to 10 and 14 percent respectively, for a dry forest type in which they persisted for up to 40 years. The current level of clearcut harvest had resulted in about the same percent of the landscape below 40 years of age, so managers assumed that they were within the natural range of variability for a forest type where the older trees being cut were 300-400 years old. However, if this pattern of maintaining 24% of the landscape in early seral stages were to continue indefinitely, stands would never exceed 160 years of age before they were cut. While the management plan may have been appropriate for some reasons, it did not conform to a reasonable interpretation of the historical range of variability.

The historical forests of the central eastern Cascades were not a solid block of late successional or old growth forests. Rather they represented a complex mosaic of patch types and structures largely mediated through disturbance patterns. The consistency shown between structural and process-oriented estimates of the historical forest conditions provide a useful template for landscape-level planning. However, such planning needs to be informed by disturbance. Our twentieth century management sought to remove natural disturbances from the landscape (Agee 1993) but only altered their frequency and intensity. Some disturbances, such as insects and diseases, increased their influence as others, such as fire, declined. Planning for a mosaic of forest structural stages in the eastern Cascades closer to the historical range of variability implies more active management of disturbance, especially fire. Increasing area burned may be a common management goal, but success will depend on ensuring that acres burned are moving the landscape closer to the historical range of variability by achieving structure-based targets. Historical range of variability outputs can be useful in defining those targets.

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