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Abstract

Fire has had a major role in shaping the forested landscapes of the American West. In recent decades, major efforts to quantify that role have been made, and characteristics of historic fire regimes have been defined: frequency, magnitude, variability, seasonality, synergism, and extent. Together, these characteristics also defined the historic landscape effects of fire in low-, moderate-, and high-severity fire regimes. Coarse-filter conservation strategies typically rely on knowledge of natural disturbance regimes to define appropriate forest structure goals, both at the stand and landscape scale, and these will differ by fire regime. Historic patch size increased across the low- to high-severity spectrum, but edge was maximized in the moderate-severity fire regime. Fire exclusion in the 20th century has caused two major types of landscape change: loss of openings in once patchy landscapes, and imposition of high-severity landscape dynamics in areas where wildfires that escape suppression now burn. Effects of historical fire regimes may be in some cases either difficult to mimic or undesirable.

Introduction

Fire has been a central theme of American forest management during the 20th century. It was the impetus for the first legislation allowing Federal forestland purchase (the Weeks Act of 1911), the first legislation allowing Federal cost-share programs to the States (Clarke-McNary Act of 1924), and the focus on impressive technology developed for purposes of fire control. The control of forest fire has been one of the most intensive natural resource investments made by government, yet paradoxically its success has resulted in a fire control problem that now commonly overwhelms firefighters (Brown and Arno 1990).

Emerging concerns related to biodiversity have stimulated efforts to favor more "natural" forms of management, emulating historical disturbances within the "natural range of variability" (Morgan et al. 1994). Biodiversity plans can be classified into coarse and fine filter approaches, and usually are a combination of both. Coarse filter approaches focus on management at the ecosystem level (Hunter 1990), with the assumption that naturally functioning ecosystem processes will create and maintain appropriate forest structures necessary for biodiversity maintenance (Karr and Freemark 1985, Attiwill 1994, Swanson et al. 1997). Where this approach leaves certain species or guilds at risk, fine filter approaches that manage at finer scale are also implemented (Hunter 1990, Haufler et al. 1996). The coarse filter approach can be successful only if the landscape ecology of natural disturbance is known, and an eventual substitution of a few coarse filter approaches for a plethora of fine-filter approaches can be justified only if the coarse filter meets the needs of the fine filter species.

The role of fire in landscape ecology is confounded by a lack of understanding of the relationships between pattern and process. Pattern, or the architecture of the forest as described by species composition and structure, including fuel amounts, size classes, and arrangement, clearly affects the manner in which the process, fire, burns. Yet the behavior of a fire is only partly dependent on pattern, as the fire behavior "triangle" includes not only fuels and topography but also weather (Agee 1997), which is marginally influenced by pattern. The objectives of this paper are to describe what is currently known about landscape character of western forest fire regimes and relate these to pattern and process, including management implications.

Fire has been the most pervasive natural disturbance factor across Western forest landscapes (Spurr and Barnes 1980), but it did not work independently of other disturbances. To avoid contradictions in scale terminology (e.g., Silbernagel 1997), fine scale will refer to minute resolution (large scale in a cartographic sense) and coarse scale will refer to broad areas (small scale in a cartographic sense). Fire has had both fine and coarse scale effects on the forests of western North America (Agee 1993), but these effects differed considerably by fire regime.

The Fire Regime

Natural disturbances range from benign to catastrophic, and can be generated from within or outside of the ecosystem (White 1987). The disturbance effects in either case are due in part to current pattern or structure and to the nature of the disturbance. Disturbance is usually characterized by a combination of factors: type, frequency, variability, magnitude, extent, seasonality, and synergism with other disturbances (White and Pickett 1985). Western forest fires have a wide range of historic frequencies from less than 10 to over 500 years that vary considerably by forest type. Predictability is associated with variability, and either very short or very long fire return intervals compared to the average interval can have major ecological effects. Non-sprouting species killed by one fire can be locally extirpated by a second closely-spaced fire; when fire intervals are unusually long, fire-sensitive species may pass through the critical period of their life history. Magnitude is often described as fireline intensity, a measure of energy output related to flame length, although other less predictable factors such as duration of smoldering can also be important. Extent describes the scale of the fire, but is generally poorly related to fire effects without knowledge of magnitude. Seasonality describes when fires occur in the year. In the American Southwest, spring months are inferred to be the most common season (Swetnam and Betancourt 1990), while in the Pacific Northwest, mid- to late summer appears to be the most common season (Wright 1996). Synergism, or the interaction of fire with other disturbances, is poorly understood and generally unpredictable. Insects, disease, and wind may follow fire events with more than endemic background effects, and conversely, accelerated fire effects may follow other disturbances. Many secondary effects such as soil mass movement may follow intense fires (Swanson 1981).

The fire regimes of western forests are usually described in terms of historical fires, and interpreted much the same way as potential vegetation (e.g., Daubenmire 1968): what occurred historically and what the trajectories of change may be with or without management (Agee 1993). Fire regimes based on fire severity (Agee 1993) are defined by effects on dominant organisms, such as trees, and although broadly described in three classes, can be disaggregated to the forest type or plant association level if desired. The approach below is to use these broader classes as an organizing paradigm within which individual forest types are discussed. The high-severity fire regimes were those in which the effect of a fire was usually a stand replacement event (Figure 1). The low-severity fire regimes were those in which the typical fire was benign to dominant organisms across much of the area it burned, while the moderate-severity fire regimes had a complex mix

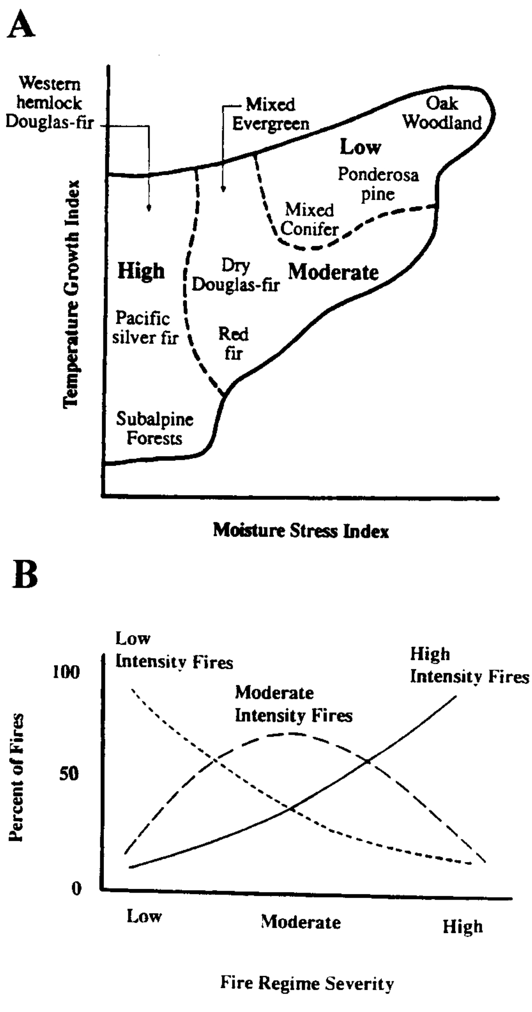

Figure 1. A. Historic fire regimes of the Pacific Northwest can be broadly defined into three categories: low-, moderate- and high-severity. Each fire regime has a number of forest types within it that have similar landscape patterns created by fire. B. Historic fire intensity and associated effects varied by fire regime.

of severity levels. These artificial classes obscure the variation that is better captured in Figure 1. Nevertheless, the landscape effects of historic fire regimes at the left, middle, and right side of the spectrum were quite different from one another.

Landscape Metrics

There are myriad metrics that may be generated for landscapes, and the important ones may differ depending on the problem (McGarigal and Marks 1994). Patch size, edge, shape, core area, nearest neighbor, and diversity metrics are among the most common. For historical fire regimes, these metrics are rarely available in quantifiable form, and because the pattern of scale is so variable, metrics are not easily compared across fire regimes. The "grain" size may be much less than 1 ha in historic ponderosa pine (*Pinus ponderosa*) forests (White 1985), but thousands of hectares in subalpine or boreal forests (Bessie and Johnson 1995). Two landscape metrics are compared below across the spectrum of Western forest fire regimes.

Patch Size

Patch size as used here refers to openings created by fire within which post-fire regeneration is likely to occur and persist. This is a subjective definition but one that helps define an ecologically significant and recognizable shift in forest structure. Patch size differs from fire extent in that a fire may spread widely across a landscape but may create conditions for regeneration only in selected locales. A large fire can be associated with creation

TABLE 1. Patch size character of western forest fire regimes.

Severity of fire regime	State/ Province	Forest type	Patch size (ha) Mean	Median	Range
Low	AZ	Ponderosa pine (Cooper 1960)	-	-	0.06-0.13
Low	AZ	Ponderosa pine (White 1985)	-	-	0.02-0.29
Low	OR	Ponderosa pine (West 1969)	.25	-	-
Low	OR	Ponderosa pine (Morrow 1985)	-	-	0.025-0.35
Low	CA	Mixed conifer (Bonnicksen and Stone 1981)	-	-	0.03-0.16
Moderate	OR	Red fir[1] (Chappell and Agee 1996)[2]	2.67	0.84	0.11-31.09
Moderate	OR	Red fir (Chappell and Agee 1996)[3]	1.34	0.39	0.12-10.08
Moderate	OR	Douglas-fir[4] (Morrison and Swanson 1990)	8.46	2.22	0.13-74.71
Moderate	OR	Douglas-fir[5] (Morrison and Swanson 1990)	11.03	2.70	0.15-253.23
High	WA/OR	Western hemlock-Douglas-fir[6] (Agee 1993)			>10,000
High	ID	Western hemlock[6] (Stickney 1986)			>10,000
High	MT/WY	Lodgepole pine-subalpine fir[6] (Romme and Despain 1989)			>10,000
High	OR	Mountain hemlock[6] (Dickman and Cook 1989)			>3,200
High	AL	White and black spruce[7] (Eberhart and Woodard 1987)			0.01-17,700

[1] red fir = *Abies magnifica*, western hemlock = *Tsuga heterophylla*, lodgepole pine = *Pinus contorta*, subalpine fir = *Abies lasiocarpa*, mountain hemlock = *Tsuga mertensiana*, white spruce = *Picea glauca*, black spruce = *Picea mariana*
[2] Goodbye fire, remeasured from maps in report
[3] Desert Cone fire, remeasured from maps in report
[4] 1893 Event Cook/Quentin Creek, remeasured from maps in report
[5] Fires of 1800-1900 Cook/Quentin Creek, remeasured from maps in report
[6] Actual patch size may have ranged from 0.01 ha spots to much larger sizes than noted
[7] Fires <20 ha were omitted from the analysis but occur in the area.

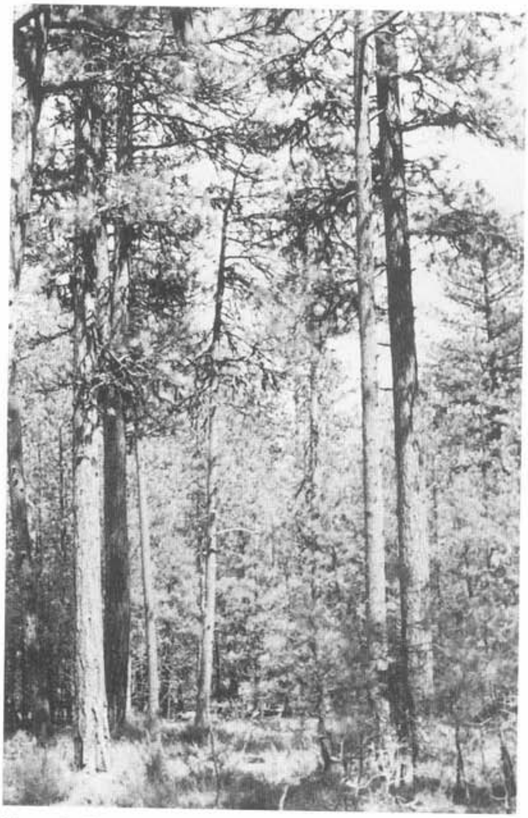

Figure 2. Ponderosa pine forest has a classic low-severity fire regime. Patches on this landscape may be as small as 0.01 ha. This pattern is disappearing across the range of the species by ingrowth of trees since the fire exclusion period and selective harvest of the older clumps of trees.

of only very small patches. The data shown in Table 1 are not a comprehensive list of patch sizes in western forests but are representative of those sizes.

The best example of large fires and small patches (regeneration) are found in the low-severity fire regimes (Figure 2). Fires burned frequently in these forests, and by regularly consuming fuels, killing small trees and pruning the boles of residual trees, maintained a relatively fire-resistant landscape across which overstory mortality from fire was rare. Forests with a large component of ponderosa pine commonly had very small patch sizes (Table 1), although historic fires commonly ranged over hundreds to thousands of ha (Wright 1996). The condition that caused the patch was in many cases senescence of an old group of trees, bark beetle attack, and subsequent consumption of the debris by fire, resulting in a range of patch sizes usually < 0.4 ha. The rest of the forest, for most ecological purposes, was a fairly uniform mosaic of mature tree clusters and grassy understories.

Larger patch sizes are typical of moderate-severity fire regimes. Although the lower end of the size range is within that of the low-severity fire regimes, much larger patch sizes also occur (Table 1). These patches are defined by the amount of mortality created by the fire, with low-severity patches underburning with little mortality, moderate-severity patches having some mortality but substantial numbers of residual trees in the larger size classes, and high-severity patches where most trees have been killed (Figure 3). The low- severity patches may appear much like the unburned forest, while the moderate-severity patches will often develop a multiple-age structure. High-severity patches will develop an even-aged structure if regeneration is immediate, or may revert to nonforest vegetation if tree seed sources are limited (Chappell and Agee 1996). Smaller patches related to canopy gaps at the scale of 0.0025-.04 ha (Taylor and Halpern 1991) also occur in these forests, and large stand replacement patches >500 ha have occurred in red fir forests in California (D. Parsons, Sequoia-Kings Canyon National Parks, pers. comm.).

High-severity fire regimes often have fire events that are driven by extreme weather (Bessie and Johnson 1995, Agee 1997). Although the majority of fires in such areas are very small, most of the area burned is from the few larger fires. They occur infrequently and in ecosystems where most or all of the trees species are not adapted to survive intense fires, so the result is usually a stand replacement fire event (Figure 4). Because fires are infrequent, forest structures are often late-successional, with multiple crown layers and high susceptibility to crown fire behavior. Wind-driven events can create patches many thousands of ha in size (Table 1). Boreal forests (Johnson 1992), subalpine forests (Agee and Smith 1984), and wet coastal forests (Heinrichs 1983) are the most widespread examples of this type of fire regime in the West. As with the high-severity patches in the moderate-severity fire regime, post-fire tree regeneration depends on seed source availability or vegetative regeneration.

Figure 3. Red fir forest has a moderate-severity fire regime. Stand replacement patches are mixed with those where thinning of the overstory dominants has occurred, and those where light underburns have no effect on the overstory at all. Patches in the foreground that appear to have a smooth canopy texture are stand replacement patches from a fire many decades old, while a new stand replacement patch is visible in the background. The rest of the landscape has burned with lower severity fire.

Figure 4. Subalpine forests, with a high-severity fire regime, may remain treeless for a century or more after being burned. Interior areas of large patches are slower to recolonize than areas near the edge where seed is more likely to blow in from adjacent unburned forest.

Patch Edge

The metric chosen to compare edge across fire regimes is the edge index used by Eberhart and Woodard (1987). They calculated the edge index by measuring the perimeter of all burned areas, including unburned "islands" within the burn, and computing a ratio between that total perimeter and the perimeter of a circle of the same area as the fire (representing the minimum edge condition). Larger values of the index represent fires with higher proportions of edge relative to patch size. This index was adapted for use here by incorporating the edge created between patches of varying severity in moderate-severity fire regimes, not just the edge between burned and unburned areas used in high-severity fires. Any edge index has inherent limitations based on image interpretation, based on the minimum patch size recognized, how many fire severity classes are defined, and the range of fire severity included in each class. In this simplified analysis, only three fire severity levels were used, based on overstory mortality, and specific edge indices are not interpreted as absolute values but as relative values comparable broadly between fire regimes.

This index could not be computed for low-severity fire regimes, because edges are diffuse except where small old patches are "decaying" and where fires may be more intense (Agee 1993). Such patches "wink" in and out as they blend with older forest patches nearby. Structural differences between a 150-year-old patch and an adjacent 250-year-old patch are so slight as to be ecologically meaningless. An edge index for low-severity fire regimes would probably be less than 1, as in any defined fire size, that could be represented as a circle of the same area, the perimeters of the small patches where fire would be intense would likely be less than the perimeter of the fire size circle (which itself would not count as "fire perimeter" because it does not necessarily create any edge).

Moderate-severity fire regimes appear to have considerably more edge than low- or high-severity fire regimes (Table 2). Because these values were taken from only a few fires, there is probably a wider range of edge index values than shown in the table, but the range from 6 to 20 suggests that moderate-severity fire regimes create substantial patchiness on the landscape. These fires typically burned for months (van Wagtendonk 1985), and burned under severe and benign fire weather, across complex topography, during the day and at night, such that substantial variation in burning conditions resulted. In addition, fuel variation caused fires to stop or slow at boundaries of previously burned areas (van Wagtendonk 1985).

TABLE 2. Patch edge character of Western forest fire regimes.

Severity of Fire Regime	Forest Type	Edge Index
Moderate	Red fir[1] (Agee and Chappell 1996)	11.66
Moderate	Red fir[2] (Agee and Chappell 1996)	6.19
Moderate	Douglas-fir[3] (Morrison and Swanson 1990)	11.16
Moderate	Douglas-fir[4] (Morrison and Swanson 1990)	21.79
High	Western hemlock/Douglas-fir (Hoh fire—500 ha—Olympic National Park)	3.72
High	White spruce-black spruce (Eberhart and Woodard 1987)	
	20-40 ha fires	2.17
	41-200 ha fires	3.29
	201-400 ha fires	3.48
	401-2000 ha fires	5.11
	2001-20000 ha fires	7.47

[1] Goodbye fire, remeasured from maps in report
[2] Desert Cone fire, remeasured from maps in report
[3] 1893 Event Cook/Quentin Creek, remeasured from maps in report
[4] Fires of 1800-1900 Cook/Quentin Creek, remeasured from maps in report

High-severity fire regimes have lower edge than moderate-severity fire regimes, but there appears to be overlap, particularly as high-severity fires become larger (Table 2). Wind-driven fires tend to be elliptical in shape rather than circular (Anderson 1983), so an edge index >1 is almost certain even in uniform terrain and fuels. Larger fires tend to be those that burn over longer periods and are associated with more weather variation and a higher probability of the head moving in more than one direction. This is likely to create more edge. In addition, larger fires tend to have larger unburned islands (Eberhart and Woodard 1987) and this is associated with increased edge effect. Simulated fire spread models for boreal forests (Ratz 1995) have produced edge index values similar to those shown for high-severity fire regimes in Table 2.

Patch Characteristics, Fire Severity, and Implications for Management

The landscape metrics of historical forests of the American West differed by fire regime (Table 3, Figure 5). Fires of large extent were common in all fire regimes, but their effects on the landscape were quite different. Fine-scale pattern was created and maintained in low-severity fire regimes, while coarse-scale pattern occurred in high-severity fire regimes. Where forest types of different fire regimes were closely juxtaposed, the characters of each intermingled (Agee et al. 1990). A small inclusion of cool, moist forest classified as a high-severity fire regime, surrounded by a much larger landscape of dry, warm forest with a low-severity fire regime, tended to have some of the character of the low-severity type: patchier, more frequent fire with smaller patch size and more edge than found where the type was widely distributed. The landscape context of the forest, including landform effects (Swanson et al. 1988), inherent edge (Yahner 1988), and the adjacent forests with their characteristic fire-induced patch

TABLE 3. Relative landscape characters of Western forest fire regimes.

Landscape Character	Fire Regime: Low-severity	Moderate-severity	High-severity
Patch Size[1]	Small (~ 1 ha)	Medium (1-300+ ha)	Large (1-10000+ ha)
Edge	Low Amount	High Amount	Moderate Amount
Pre-Post Fire Similarity[2]	High	Moderate	Low

[1] The average patch within which tree regeneration will be open-grown.

[2] Of the total area burned, the proportion resembling the pre-fire forest structure.

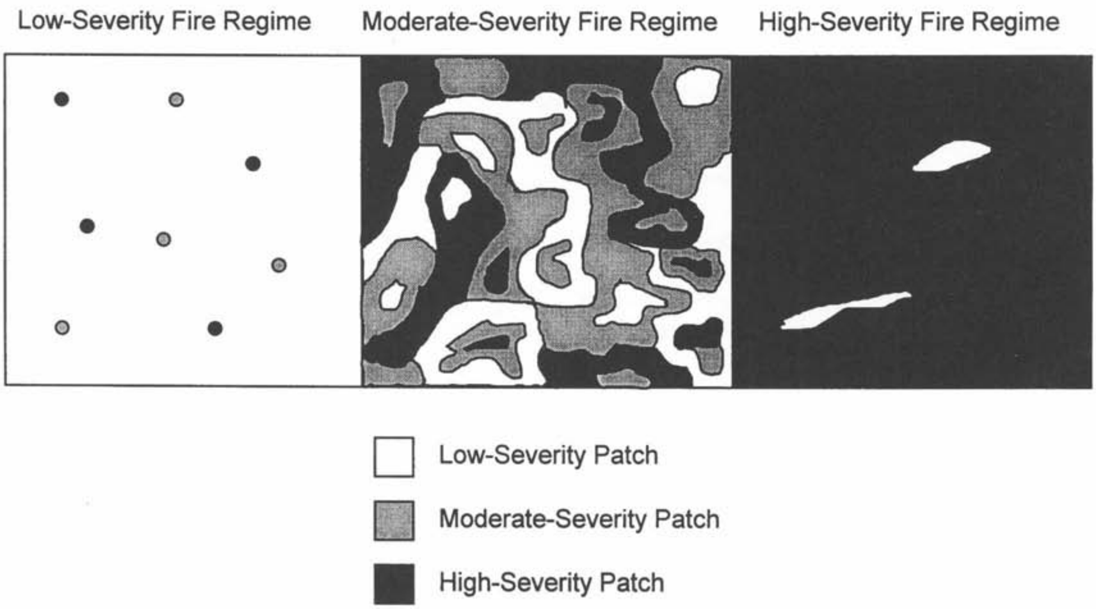

Figure 5. A schematic of landscape pattern of fire regimes. Black dots in low-severity fire regimes are very old patches of large, old trees being killed by insects and decomposed by fire, and gray dots are emerging pole-size stands that have less-defined edge. The moderate-severity fire regime is typically a complex mosaic of larger patches of the three fire severity levels, while the high-severity fire regime has large stand replacement patches.

and edge patterns, is important in understanding the historic landscape character of a forest type.

The predominance of pattern versus process as controlling factors of fire and forest landscape dynamics will vary by fire regime. Most theoretical approaches to disturbance and forest pattern have simplified disturbance and fire to a binary process: a landscape cell is either disturbed or not (e.g., Turner et al. 1989). These models have utility in high-severity fire regimes (Turner and Romme 1994, Ratz 1995), but have less utility for moderate- and low-severity fire regimes, and present scaling problems when applied to real landscapes. In the low- and moderate-severity fire regimes, fires spread widely but had significant pattern effects on only medium to small portions of the landscape, and the control of process by pattern is obvious. Frequent, low-intensity fires created temporary fire barriers by consuming fuels, and resulted in a jigsaw-like shape of subsequent fires. This has been shown by Wright (1996) for ponderosa pine, a low-severity fire regime, and by van Wagtendonk (1985) for red fir, a moderate-severity fire regime. Pattern, as represented by age-class distribution and spatial structure, was so fire-tolerant in low-severity fire regimes that while the forest was dependent on fire in the long run to maintain its pattern, it was relatively immune to severe short-term effects; the interaction of pattern and process resulted in a quasi-stable system. While a true equilibrium system with balanced age classes has not been shown even for ponderosa pine (Cooper 1960), the low-severity fire regimes were much more stable than high-severity fire regimes.

Under "normal" weather, pattern has also been shown to control process in high-severity fire regimes. Naturally-occurring fires in older forests at Yellowstone National Park, between 1972 and 1987, tended to slow or stop at boundaries of young forest with simpler, less fire-prone structure (Despain and Sellers 1977, Romme and Despain 1989). However, very large historic fires appear to have been the source of much of the widespread, older forest (Romme 1982), indicating that process must have overwhelmed pattern at some distant time in the past. The Yellowstone fires of 1988 burned forests of all ages, indicating that process overwhelmed pattern (Romme and Despain 1989), which has also been documented for Canadian subalpine forests (Bessie and Johnson 1995). While an individual stand may appear stable over time to a human observer, the landscapes of high-severity fire regimes (a specific spatial scale) over the lifespan of a tree (a specific temporal scale) are considered non-equilibrium systems (Baker 1989, Turner and Romme 1994) because of the nature of the disturbance process: infrequent, large, severe fires that have a persistent effect (centuries-long) on landscape pattern.

Modern forestry has had significant effects on landscape pattern, but probably the most pervasive effect has been that of fire exclusion. Effects of fire exclusion are extensive in low-severity fire regimes (Weaver 1943), less in moderate-severity fire regimes, and least in high-severity fire regimes, because fire has been removed for more fire-return intervals in low- and moderate-severity fire regimes than in the high-severity fire regimes. By allowing forest patches in low-severity fire regimes to converge in structure, developing multi-layered character with increased fuel loads, the infrequent wildfire that escapes control under severe weather conditions now has much more severe effects (Agee 1997). Forest openings, once characteristic of many fire-prone landscapes, have decreased in size as surrounding forests have become more dense (Skinner 1995). Much of the induced edge that persisted in a shifting mosaic through the 19th century is now a subtle edge between mature and old-growth forest (Morrison and Swanson 1990), and these landscapes are now more prone to high-severity fire. A persistent but more unstable landscape pattern is being created, not only in patch metrics but in susceptibility to future severe fire. Higher proportions of post-fire regeneration in sprouting hardwoods and serotinous-coned pines will be more likely to be killed by future fires than the more fire-tolerant mature pines, larches (*Larix occidentalis*), and Douglas-firs (*Pseudotsuga menziesii*) they replace.

Wide riparian forest buffers are being prescribed for some western forests. While they have been defended on the basis of protection for aquatic organisms, including endangered fish, corridors for wildlife, and sources of coarse woody debris for future stream habitat, they have also been documented, under some conditions, as corridors for severe wildfire (Segura and Snook 1992, Agee, pers. obs.). There are few data with which to evaluate the flammability of riparian zones. More complex structures often do occur in riparian zones, but these may be due to better site quality, allowing faster post-fire succession, or to less frequent or lower severity fire in these sheltered locations (Romme and Knight 1981). In the dry eastern Washington Cascades, high-elevation forest refugia (areas less likely to burn) were identified as occurring above 1500 m elevation on north aspects, and often adjacent to the confluences of perennial streams (Camp et al. 1997). In northern California mixed-evergreen forest, late-successional forest structure is most likely to be found in lower slope positions and on north and east aspects (Taylor and Skinner in review). Conversely, in western Idaho, riparian zones in some locations have burned more severely than associated uplands (Figure 6). Clearly, complex interactions are occurring between process, pattern, and landscape position of riparian forests, and need to be evaluated in more depth.

The concept called "natural range of variability" has been proposed as an appropriate coarse filter approach to ecosystem management. Simulating natural disturbance processes and patterns is one way to maintain broadly-defined ecosystem productivity (Attiwill 1994, Swanson et al. 1997). In most Western forest ecosystems, there is still enough residual evidence in live trees and stumps to allow reconstruction of historic landscapes over time (Agee, 1993, Wallin et al. 1996). In high-severity fire regimes, Baker (1994) suggested that reintroducing the process of fire might itself be sufficient to restore the natural pattern. In low-severity fire regimes the issue has been debated (Bonnicksen and Stone 1982, Parsons et al. 1986), but the debate has centered more on objectives of pattern or process rather than whether some type of reconstruction was desirable. Although these debates were first associated with natural areas, the trend towards coarse filter conservation strategies for many forest lands has expanded the potential implications of these arguments to much of the forested land of the West. There is no "right answer" in these arguments, but it is clear that in low-severity fire regimes, modification of fuel structures by underburning or thinning will move the system towards a more natural pattern. Continuing to remove large green trees in conjunction with salvage logging will exacerbate current conditions (Agee 1997). In moderate-severity fire regimes, timber harvesting that moves away from traditional large clearcuts to (a) partial cuts, (b) small patch cuts with snag retention, and (c) a system of reserves, utilizing prescribed fire even in reserves, will create more natural pattern than either past management or a pure reserve system with no recognition of process. In high-severity fire regimes, large patch sizes, although perhaps historically present, will be difficult to manage for and may be perceived as a "catastrophe best to be avoided" (Hunter 1993). When the severe weather event occurs, we may not have as much control over nature as we think, so large patch sizes will probably occur in these systems regardless of our desires.

Figure 6. Portions of the riparian zone of Little French Creek, Payette National Forest, Idaho, burned much more severely than adjacent uplands. The riparian zone (A) had substantial dead Engelmann spruce (*Picea engelmannii*) and multilayered structure, and burned with a crown fire. The upland forest (B), which had burned in ca. 1900 and again in 1933, was composed of self-pruned, widely spaced lodgepole pine with a huckleberry (*Vaccinium scoparium*) understory and little coarse woody debris, and spot fires here did not spread (U.S. Forest Service photo by Morgan Beveridge).

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