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The Relative Impact of Harvest and Fire upon Landscape-Level Dynamics of Older Forests: Lessons from the Northwest Forest Plan

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Abstract

Interest in preserving older forests at the landscape level has increased in many regions, including the Pacific Northwest of the United States. The Northwest Forest Plan (NWFP) of 1994 initiated a significant reduction in the harvesting of older forests on federal land. We used historical satellite imagery to assess the effect of this reduction in relation to: past harvest rates, management of non-federal forests, and the growing role of fire. Harvest rates in non-federal large-diameter forests (LDF) either decreased or remained stable at relatively high rates following the NWFP, meaning that harvest reductions on federal forests, which cover half of the region, resulted in a significant regional drop in the loss of LDF to harvest. However, increased losses of LDF to fire outweighed reductions in LDF harvest across large areas of the region. Elevated fire levels in the western United States have been correlated to changing climatic conditions, and if recent fire patterns persist, preservation of older forests in dry ecosystems will depend upon practical and coordinated fire management across the landscape.

Key words: disturbance; fire; landsat; forest management; Northwest Forest Plan; old growth.

Introduction

Changing views of the ecological, economic, and societal values of older forest ecosystems have led to significant changes in forest management in the last few decades. In the Pacific Northwest (PNW) of the United States, the Northwest Forest Plan (NWFP) was enacted in 1994 partly because of growing concern that losses of older forests had put at risk the survival of species dependent on those forests (for example, the northern spotted owl, *Strix occidentalis*, USDI 1992). The NWFP amended the management plans of federal lands in the region,

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and we know that it led to a significant decline in the harvest of older forests on federal lands (Mouer and others 2005). However, a complete characterization of losses of old forests across all ownerships has been lacking. Consequently, we do not know the degree to which significant federal policy changes affecting approximately half of the region's forests have altered older forest dynamics at the landscape level. Further, we do not know how the effects of federal harvest reductions compare to the effects of fire, particularly because wildland fire has generally increased in the western United States in the time since the implementation of the NWFP (Westerling and others 2006). We used a 30-year satellite record to identify trends in losses of large-diameter forests (LDF) to both harvest and fire across all lands in the western Oregon and Washington portions of the NWFP. This allowed assessment of the effects of the NWFP relative to other landscape factors at a variety of spatial and temporal scales. It was hoped that this assessment might provide insight into the ability of a large landowner to impact the fate of older forests across a landscape.

In assessing the effects of federal policy changes, context regarding the actions of neighboring landowners and the effects of natural disturbance is critical. Policies that ignore forest conditions on other ownerships, or that make assumptions that are not based on data, can have unintended consequences at the regional level (Spies and others 2007). For example, one might expect increased harvesting of older forests on private lands if some owners remove trees to avoid being subject to Endangered Species Act restrictions or if, in the absence of federal harvests, timber prices increased significantly. Likewise, natural disturbances can dramatically alter regional patterns of older forests in a manner relatively independent of harvest practices. The effect of a particular owner's harvest reductions cannot be understood at the landscape level in isolation of factors such as fire and neighboring landowners.

Other studies (Bolsinger and Waddell 1993; Kennedy and Spies 2004; Strittholt and others 2006) have assessed the historical distribution of older forests across the region and have pointed out large losses in pre-settlement or early 20th century stocks of older forests. However, the relatively coarse temporal grain of these studies has not allowed discrimination of finer-scale trends in, for example, the loss of older forests for periods immediately preceding and following passage of the NWFP in 1994. Although regional harvest volume records (for example, ODF 1989–2002) and previous satellite-enabled disturbance detection (for example, Cohen and others 2002; Franklin and others 2002; Healey and others 2006) identify general disturbance trends with reasonable temporal specificity, data specific to older forests are scarce.

The Landsat series of satellites has allowed consistent and continuous monitoring of both forest structure and change since 1972 (Cohen and Goward 2004), and use of Landsat imagery here enabled the monitoring of disturbance processes specifically in stands with large trees. This analysis was carried out across watershed, province, and regional scales. Better understanding of the role of federal harvest levels in preserving older forests, especially in the context of non-federal forest management and natural disturbance such as fire, may be useful to managers in other regions as they work toward landscape-level forest composition goals.

Methods

Study Area

The study area comprised the Oregon and Washington portions of the recognized range of the northern spotted owl. This area and a corresponding portion of northwestern California make up the region covered by the NWFP. A range of coniferous

Figure 1. Physiographic provinces used in this analysis to geographically segment the study area. Provinces included: Olympic (OLY), Western Lowland (WLO), West and East Cascades Washington (WCW and ECW), West and East Cascades Oregon (WCO and ECO), Willamette (WIL), Coast Range Oregon (COA), and Klamath (KLA).

Table 1. Area of Forest (hectares $\times 10^{-3}$) in Each Physiographic Province by Owner

	ECO	WCO	COA	ECW	KLA	OLY	WCW	WLO	WIL	Total
Bureau of Land Management (federal)	18	270	315	0	319	0	0	0	7	928
Fish and Wildlife/National Park Service (federal)	30	34	0	54	0	327	262	2	0	710
Forest Service (federal)	561	1,482	239	1,280	477	250	1,149	0	0	5,438
City/County	0	5	20	0	14	5	36	36	0	117
State	1	22	274	158	9	170	269	249	1	1,154
Tribal	102	8	6	286	0	95	0	33	0	529
Private industrial	81	529	856	63	266	221	461	803	29	3,309
Private non-industrial	77	137	273	40	191	77	149	669	92	1,706
Private unknown	0	0	0	279	0	0	1	61	0	341
Total	870	2,487	1,982	2,160	1,277	1,145	2,327	1,854	130	14,231

forest types occurs in the study area; Franklin and Dyrness (1973) summarized the climatic and edaphic factors that affect the biogeography of the region's forests. Nine physiographic provinces (Figure 1), introduced by Franklin and Dyrness (1973) and later modified and adopted by the Forest Ecosystem Management Team (1993), were used to describe sub-regional trends. Western provinces, which in general receive more precipitation, include: the Olympic (OLY), Oregon Coast (COA), Western Lowlands (WLO), the Willamette Valley (WIL), and the Western Cascades of Oregon (WCO) and Washington (WCW). Drier provinces include: the Klamath (KLA) and East Cascades provinces of both states (ECO and ECW). Regional analyses of disturbance performed in this study used these physiographic provinces in addition to hydrologic subbasins (4th field watersheds) to identify spatial trends within the region. Forest ownership, as derived from tax plat records compiled by Atterbury and Associates, is unevenly distributed among provinces (Table 1). In agreement with other studies (for example, Stinson and others 2001), private non-industrial forest owners were distinguished from industrial owners if their forestland totaled less than 405 ha (1,000 acres). Smaller parcels were labeled as ''industrial'' if they were registered to entities, such as Timber Investment Management Organizations, with regional holdings of at least 405 ha. The area of non-public reserved land in the region was small relative to the groups listed in Table 1 and these lands were not considered in this analysis.

Creation and Validation of the 1972-era Map of Older Forests

Although 1972-era forest inventory data are available for some parts of the study area, the geographic coordinates associated with those data are generally of insufficient accuracy for use in remote sensing. Pin-pricked plot photos may be used in concert with geo-referenced historical imagery to deduce plot locations, but this process is laborious and is limited to areas where plot data survive. Because adequate training data from the early 1970s were unavailable, training data were instead developed using basic assumptions involving a map of later forest conditions. Mouer and others (2005) used regression-based methods to predict QMD (quadratic mean diameter) of dominant canopy and sub-dominant canopy trees throughout the region from a combination of 1996 Landsat Thematic Mapper (TM) imagery, diameter data from approximately 6,500 plots throughout the study area, and topographic variables. Contiguous areas in this map having QMD greater than 20 in. (50.8 cm) were used to train classification of the 1972 imagery. The 20-in. threshold was similar to that suggested by the NWFP Record of Decision (USDA and USDI 1994) as characteristic of late-successional and old-growth forest (80+ years old). Although forest conditions certainly changed between the acquisition of the 1972 imagery and the 1996 QMD map, forests meeting the late successional and old-growth criteria in 1996 were nevertheless taken to be acceptable indicators of older forests 24 years earlier.

The image series used in this analysis was acquired by different Landsat sensors at different times (Appendix A). The 1972 and 1977 datasets were acquired by Landsat Multispectral Scanner (MSS) instruments and had lower spatial resolution (79 m ground distance) than later imagery, which was acquired by Thematic Mapper (TM) and Enhanced Thematic Mapper (ETM+) sensors (30 m). All imagery was geometrically re-sampled to a 25 m cell size to facilitate convenient multitemporal analysis. The imagery used to produce the 1972-era map of older forests was enhanced using the Tasseled Cap transformation (Kauth and Thomas 1976) to highlight spectral features relevant to forest structure (Cohen and Spies 1992). A supervised maximum likelihood classification algorithm was used on a per-scene basis with multiple training sites from the 1996 map in every scene. Classification results were submitted to a 3 × 3 majority low-pass filter to reduce ''speckle'' associated with radiometric noise, and were then merged to create a regional map.

Because the training data for this classification were drawn from a 1996-era map, assessment was needed regarding the actual circa-1972 size classes captured in this map of older forests. Pin-pricked aerial photos from 120 inventory plots, randomly selected from available plot data covering the Gifford Pinchot, Mt. Baker, Mt. Hood, and Deschutes National Forests and representing a wide range of QMDs, were used to geo-register plot data to the map. It should be emphasized that the available plot data were not a systematic sample of the entire region, and notably did not include plots from the Klamath region, an area with many unique floristic and edaphic attributes (Franklin and Dyrness 1973). QMDs were calculated from the plot data and compared to corresponding classification (older forest or not) majority values extracted from a 1-ha window around the plot center. Results of this comparison (Figure 2) showed inclusion in the older forest map of many stands falling below the 50.8 cm QMD threshold used in the Moeur map of late-successional and old-growth forest.

A likely factor in the inclusion of smaller forests in the 1972-era older forest class was the temporal mismatch involved in identifying older forest training sites from a 1996 map; some stands just passing the approximately 80-year age threshold in the 1996 map were actually slightly more than 50 years old in 1972. Thus, the older forests studied in this paper corresponded roughly (in 1972) to the ''mature'' (50–150 years) and ''old'' (>150 years) classes used by Strittholt and others (2006) and Jiang and others (2004). Such stands were termed here ''large-diameter forest'' (LDF) because their definition was based solely on canopy tree size. As such, LDF may range from late-successional stands dominated by shade-tolerant species to mature second-growth plantations containing large trees. In the assessment of Strittholt and others (2006) using circa-2000 data, the proportion of old growth within the combined ''mature'' and ''old'' forest category (similar to LDF) ranged from approximately 11% in the populous Willamette Valley to 43% in the region's drier provinces to over 70% in the predominantly reserved North Cascades area. Thus, very old forests make up a spatially variable subset of the forests labeled here as ''LDF.''

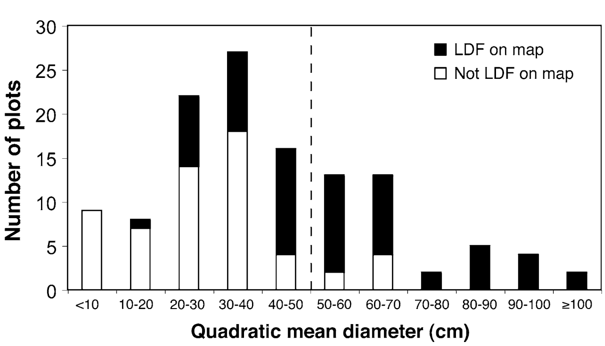

Figure 2. Comparison between mapped 1972 LDF condition and reference data. Inventory plots from the period (1968–1974) were geo-registered to the map and plotted here according to their measured QMD and class label. The vertical dashed line indicates the threshold used here (50.8 cm) to define LDF. Although most actual LDF was correctly mapped, some larger non-LDF was mislabeled as LDF.

Creation and Validation of the 1972–2002 Stand-Clearing Disturbance Map

Removals of LDF by stand-clearing harvests, fires, and volcanic activity between 1972 and 2002 were

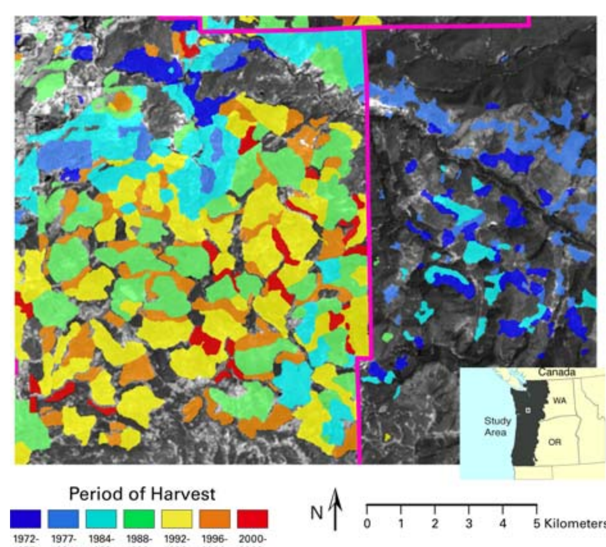

Figure 3. Stand-clearing disturbances from 1972 to 2002 were mapped throughout the study area (inset) using time series of Landsat satellite imagery. This subset of the map (displayed over an aerial photo for context) illustrates how harvest patterns have varied over time and across owners. The magenta line is an ownership boundary between industrial forest land (left) and a federal national forest (right). Although industrial harvests have been continuous throughout the study period, federal harvests ceased in the period leading up to the NWFP (late 1980s).

mapped (Figure 3) using the Landsat imagery from 1972, 1977, 1984, 1988, 1992 (1991 in Oregon), 1996 (1995 in Oregon), 2000, and 2002 (Appendix A). Stand-clearing disturbances were defined as those removing all or nearly all canopy cover from a previously forested stand. Though less severe fires can certainly affect LDF, and partial harvests represent over 60% of the removals on this landscape (by area; Smith and others 2004), not all such events result in a loss of LDF. The classification approach used in this analysis focused on stand-clearing events because they could be mapped unambiguously and consistently across different ownerships and over time, allowing a relatively accurate characterization of how natural and human-caused disturbances have altered the region's LDF.

This map represented an update and expansion of a map of disturbances in COA, KLA, WCO, and WIL from 1972 to 1995 that was summarized by Cohen and others (2002). The map was produced through multi-temporal composite analysis (Coppin and Bauer 1996). In this process, spatially co-registered spectral layers from several time periods are classified simultaneously to identify areas cleared between image dates. Spatial co-registration was achieved through the manual and automatic (Kennedy and Cohen 2003) pair-wise co-location of tie points in both an image chosen as a reference date and each individual image in the time series. Polynomial geometric transformation was then carried out to register all dates to the spatial reference date; root mean square errors in this process were generally less than 30 m.

The classification method used to identify disturbance in the portion of the map reported by Cohen and others (2002) relied on unsupervised classification in an iterative ''cluster-busting'' approach. An alternative classification scheme was used for the 1995–2002 periods in this area as well as for all time periods (1972–2002) in the rest of the study area (ECO, OLY, WCW, WCW, and WLO). This alternative approach used supervised classification, in which disturbed areas were identified based on the maximum likelihood similarity of their multi-temporal spectral signatures with those of manually identified training sites. The inputs for this process were the two Tasseled Cap indices for the MSS (1972–1984) imagery and a single-band (per image date) transformation called the Disturbance Index (DI; Healey and others 2005) for the TM and ETM+ (1984–2002) imagery. This supervised classification approach required significantly less processing time than previous methods.

Composite analysis proceeded on a scene-by-scene basis, and the results were mosaicked to provide a regional map of stand-clearing disturbance. Fires were manually distinguished from harvests using their irregular spatial characteristics supported by ancillary fire records. Pixels having been, according to composite analysis, disturbed more than once in the map's seven time periods were coded in a way that identified each disturbance. In composite analysis, slight spatial misalignment of imagery from different dates can cause false-positive change along forest—non-forest boundaries. To minimize this problem and other phenomena associated with radiometric artifacts, post-process filtering was used to remove small, isolated patches of apparent change. A 3 × 3 low-pass majority filter was passed over the map, and a GIS (Geographic Information System) process was then performed that merged groups of pixels smaller than 2 ha into surrounding classes. Thus, the minimum mapping unit of disturbances in this map is 2 ha. A forest cover mask (O'Neil and others 2000) was used to minimize errors caused by agricultural land that may have undergone inter-annual spectral changes resembling disturbances. The single date of this mask (1996), however, precluded detection of pre-1996 land-cover change, an omission which would have the greatest effect in analysis units close to population centers.

Error assessment of the disturbance map was conducted at 2,648 randomly selected points throughout the region. The sampling scheme ensured that at least 40% of the assessment points fell on pixels mapped as disturbed, with no two assessment points permitted in the same disturbance patch. Mapped disturbance values for each selected pixel were compared to reference values determined through visual inspection of the multi-temporal Landsat imagery used to produce the map. Stand-clearing disturbances create distinct and relatively unambiguous spectral changes in a forest, allowing highly accurate visual interpretation of a point's disturbance status using Landsat imagery (Cohen and others 1998). In some parts of the map, accuracy was assessed by the same workers who created the map, which may have exercised an upward bias on accuracy estimates. To minimize this possibility, assessments of disturbance status were ''blind'' with respect to mapped values. Because sample points were given unequal probabilities of selection (due to the requirement that 40% of the sample points fall in disturbed classes), the Kappa and overall accuracy statistics were calculated from an adjusted matrix of reference versus mapped disturbance dates and types. This adjustment was accomplished by weighting each change category in proportion to its occurrence on the map.

Analysis of Maps

Loss of LDF over time was derived by combining the maps of 1972-era LDF and 1972–2002 stand-clearing disturbance in a GIS. Further analyses were supported by the overlay of other spatial layers, including: a regional map of ownership provided by Atterbury and Associates, the map of the physiographic provinces shown in Figure 1, and a map of hydrologic subbasins provided by the US Environmental Protection Agency. Rates of LDF loss were calculated for each interval and each analysis unit (ownership group, province, subbasin) by dividing the amount of mapped LDF loss by the number of years between image acquisitions. The last period (2000–2003) was counted as 2.3 years for these purposes because imagery in 2002 was systematically acquired 2–3 months later than the typically mid-summer imagery acquired for other years.

Results

Accuracy of Change Detection

The overall accuracy of the 1972–2002 stand-clearing disturbance map was 90.7% when adjusted for unequal sampling probabilities, with an adjusted kappa coefficient of 0.76 for 15 classes (7 dates of harvest and fire, plus ''no change'') (Table 2). Errors were well distributed among classes in the map except that the first three periods, corresponding to the period based upon MSS imagery, had somewhat lower levels of accuracy than other periods. It is possible that the relatively long remeasurement intervals (5, 7, and 4 years) during this period may have led to decreased accuracy; other studies (Healey and others 2005; Jin and Sader 2005; Masek and others 2008) have shown better change detection results with shorter intervals. However, errors were no greater in the longest interval during this period, 1977–1984, than during other periods. Limitations related to the MSS sensor itself were the most likely cause of lower accuracy prior to the TM period. In addition to lower spatial resolution, MSS lacked a shortwave infrared sensor, which has been critical in studies of forest structure (Cohen and Goward 2004). Errors of omission and commission were notably balanced throughout the study period, suggesting no systematic bias with respect to estimates of the area of disturbance. Map results corresponded well to available regional-scale harvest statistics. The map indicated that stand-clearing harvest on federal land from 1996 to 2002 affected 2,237 ha/year. Federal harvest records (from data supporting Baker and others 2005, C. Palmer personal communication) showed that regeneration harvests for the corresponding area covered 2,150 ha/year over approximately the same period (1995–2003).

Harvest Patterns

Harvest of LDF in the study region rose in the late 1970s through the late 1980s and then fell both in absolute terms and as a proportion of remaining LDF during the 1990s (Figure 4). The decline of LDF harvest on federal land (FS and BLM in Figure 4) was particularly abrupt following the development of the NWFP. Federal stand-clearing harvest made up 32% (by area) of all stand-clearing harvests of LDF in western Oregon and Washington prior to the NWFP (1992 in our map) and less than 8% in 1992 and later (Figure 5A).

The LDF and disturbance maps showed that a significant fraction of the region's older forests were found on state and private lands (39% in 1972, 32% just prior to the NWFP in 1992, and 28% at the end of 2002). Strittholt and others (2006) estimated non-federal ownership of ''mature and old-growth forests'' to be 36% in 2000. The reduction in the rate of LDF loss on non-federal land following 1992 (from 388,000 to 249,000 ha/decade) was actually greater than the reduction on federal land, but exhaustion of available inventory was likely a significant factor in this drop. When expressed as the percentage of remaining 1972-era LDF removed, non-federal LDF harvest rates were almost unchanged following the NWFP, moving from 20% to 18% per decade (Figure 5B). Much of the non-federal LDF harvest depicted in Figure 5B was carried out by private industrial owners, who had harvested 64% (715,000 ha) of their 1972-era LDF by 2002 (representing 52% of all LDF harvest in the region). Tribal owners were the only major ownership group to increase LDF harvest in the 1990s. This increase was centered largely in the Yakama nation in south-central Washington, where a western spruce budworm (*Choristoneura occidentalis*) outbreak was aggressively treated and salvaged (Petruncio and Lewis 2005). LDF harvest rates on state and non-industrial private land following the NWFP were approximately equal to removal rates of the 1970s (approximately 1% of remaining LDF per year); these rates were below peaks of the

Table 2. Accuracy Matrix of the 1972–2002 Map of Stand-Clearing Disturbances, as Measured with Randomly Selected Points that were Visually Assessed with Landsat Imagery

Map	Reference																
	No change	Cut 72–77	Cut 77–84	Cut 84–88	Cut 88–91	Cut 91–95	Cut 95–00	Cut 00–02	Fire 72–77	Fire 77–84	Fire 84–88	Fire 88–91	Fire 92–95	Fire 95–00	Fire 00–02	Total	
No change	1,420	18	21	23	16	5	15	2	1	1	2	1	3	3	2	1,533	0.93
Cut 72–77	18	84	6	1	0	0	0	0	3	1	0	0	0	0	0	113	0.74
Cut 77–84	22	8	160	3	0	0	0	0	0	2	0	0	0	0	0	195	0.82
Cut 84–88	22	1	1	166	2	1	1	1	0	0	0	0	0	0	0	195	0.85
Cut 88–91	11	2	1	3	135	3	2	0	0	0	0	1	0	0	0	158	0.85
Cut 91–95	12	0	0	0	1	107	3	0	0	0	0	0	0	0	0	123	0.87
Cut 95–00	19	1	0	0	0	1	113	1	0	0	0	0	0	0	0	135	0.84
Cut 00–02	6	0	0	0	0	0	4	70	0	0	0	0	0	0	0	80	0.88
Fire 72–77	1	0	0	0	0	0	0	0	3	0	0	0	0	0	0	4	0.75
Fire 77–84	0	0	0	0	0	0	0	0	0	15	0	0	0	0	0	15	1
Fire 84–88	2	0	0	0	0	0	0	0	0	0	12	0	0	0	0	14	0.86
Fire 88–91	0	0	0	0	0	0	0	0	0	0	0	12	0	0	0	12	1
Fire 92–95	2	0	0	0	0	0	0	0	0	0	0	0	18	0	0	20	0.9
Fire 95–00	6	0	0	0	0	0	0	0	0	0	0	0	0	19	0	25	0.76
Fire 00–02	5	0	0	1	0	0	0	0	0	0	0	0	0	0	20	26	0.77
Total	1,546	114	189	197	154	117	138	74	7	19	14	14	21	22	22	2,648	
	0.92	0.74	0.85	0.84	0.88	0.91	0.82	0.95	0.43	0.79	0.86	0.86	0.86	0.86	0.91		0.89

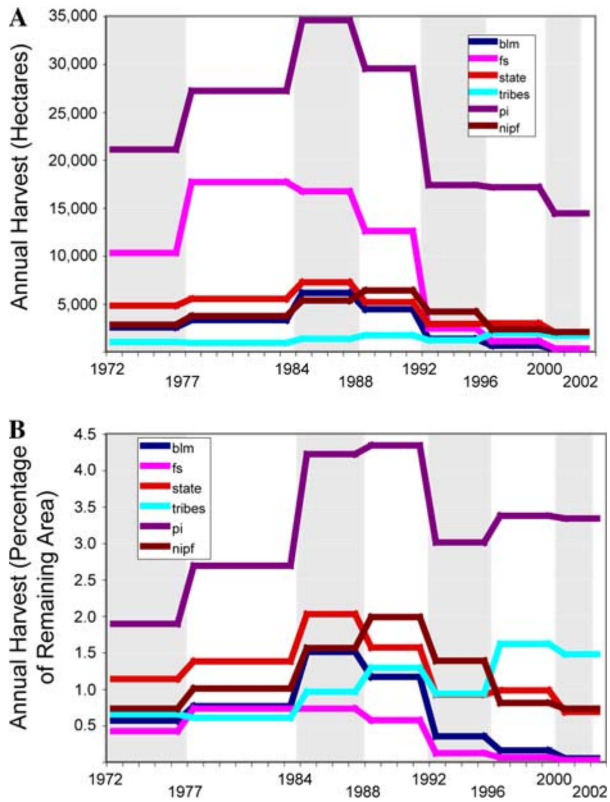

Figure 4. Stand-clearing harvest of LDF by different owners over time. Annual levels of LDF harvest are shown in terms of area (**A**) and as a fraction of remaining LDF (**B**) for major ownership groups over time. Ownership groups include: the Bureau of Land Management (blm), the Forest Service (fs), Oregon and Washington State (state), native American (tribes), private industry (pi), and non-industrial private owners (nipf). Harvest rates are shown on a per-year basis calculated from seven mapped intervals: 1972–1977, 1977–1984, 1984–1988, 1988–1992, 1992–1996, 1996–2000, 2000–2002.

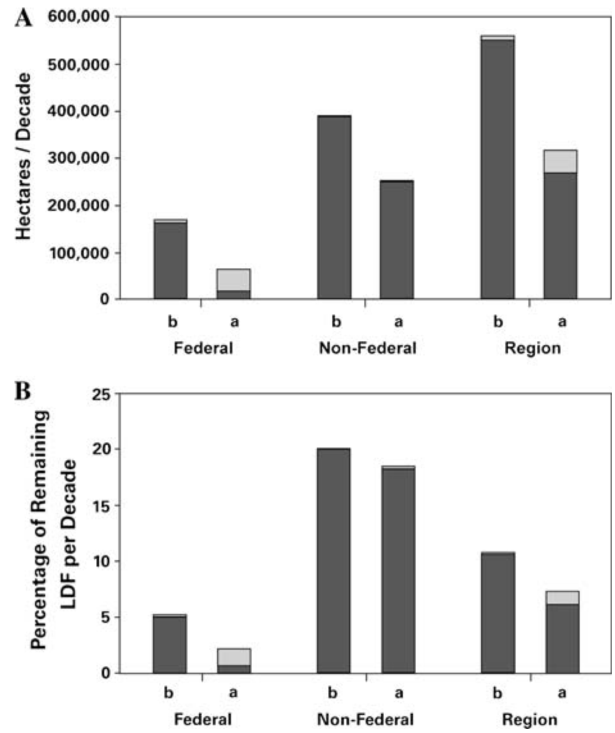

Figure 5. The rate of mapped LDF loss within and outside of federal forests both before the NWFP (1972–1992) and subsequently (1992–2002). LDF loss is expressed both in hectares/decade (**A**) and as a percentage of remaining LDF in each ownership group (**B**). LDF losses to both harvest (dark gray) and fire (light gray) are shown. The time period is indicated below each bar with either a ''b'' (before NWFP) or an ''a'' (after NWFP).

1980s and considerably below the harvest levels of industrial private owners (Figure 4).

Spatial patterns of LDF harvest were strongly related to ownership patterns (Table 1) at the province level, with large declines in post-NWFP LDF harvest in moist provinces dominated by federal lands (that is, the Olympic and Western Cascades Provinces, Figure 6A). Large absolute decreases in harvest rates were also mapped in moist provinces dominated by private lands (COA and WLO), but harvest rates in these areas were relatively steady when measured as a percentage of remaining LDF (Figure 6B). In these provinces, liquidation of remaining 1972-era LDF continued at a rate (11% per decade in COA and 22% per decade in WLO) much higher than the regional average (6% per decade). An apparent increase in LDF harvest in WIL (Figure 6) was likely exaggerated by the unmonitored pre-1996 land-use change discussed earlier, particularly given the province's small area of LDF and the fact that it was the site of most of Oregon's land-use change during the 1970s and 1980s (Lettman and others 2002).

The dry East Cascades provinces, which are predominately federal, were among the most lightly harvested provinces prior to the NWFP, and harvest intensity in those provinces declined only slightly after 1992. In the Washington East Cascades Province, decreasing federal LDF harvests were offset by the insect-related salvage operations on tribal land described above. Subbasin-level patterns mirrored province-level patterns with respect to ownership; the highest rates of LDF harvest both before and following the NWFP occurred in the predominantly private regions in southwestern Washington and in the Coast Range of Oregon (Figure 7). In most of the subbasins depicted in Figure 7 (67 out of 86), LDF harvest decreased following the NWFP, with an average drop in the harvest of remaining LDF of

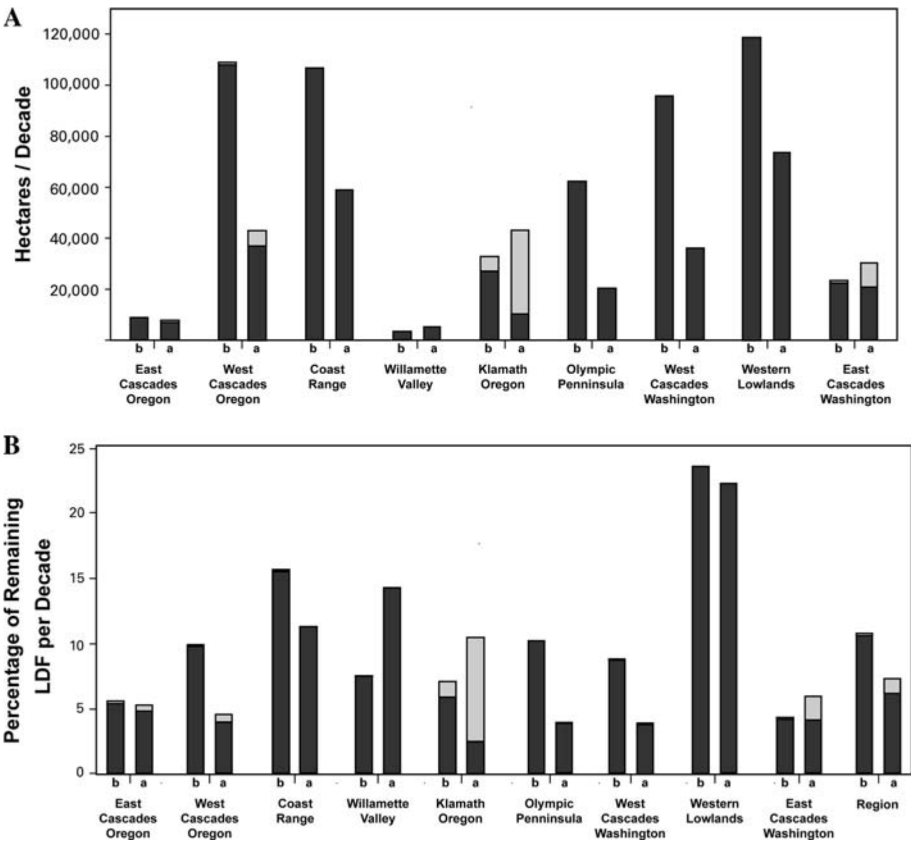

Figure 6. The rate of mapped LDF loss for each physiographic province in the study area both before the NWFP (1972–1992) and subsequently (1992–2002). LDF loss is expressed both in hectares/decade (**A**) and as a percentage of remaining LDF in each ownership group (**B**). LDF losses to both harvest (dark gray) and fire (light gray) are shown. The time period is indicated below each bar with either a ''b'' (before NWFP) or an ''a'' (after NWFP).

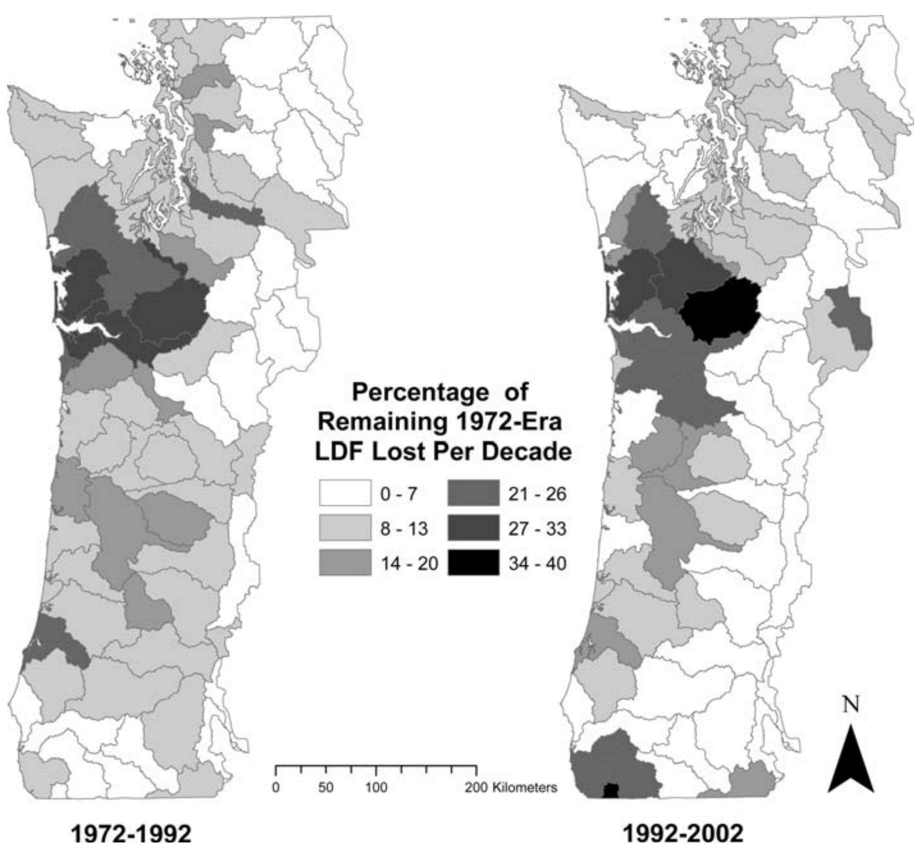

Figure 7. Rates of LDF loss by subbasin before and after the NWFP. The decadal rate of all LDF loss, as a percentage of remaining LDF, is displayed at the subbasin level for 1972–1992 and 1992–2002. Although the effect of decreasing federal harvests can be seen in the federally dominated central part of the map, local increases due to fire are evident in some dry subbasins in the eastern and southern parts of the region.

1.4% per decade. Following the NWFP, the amount of harvest in a subbasin was strongly correlated with the amount of federal ownership ($r^2 = 0.63$; Figure 8). However, variation occurred in harvest rates of largely non-federal subbasins because of differing composition of ownership. The Lake Washington and Lower Cowlitz subbasins (highlighted in Figure 8), for example, were each predominantly non-federal but had contrasting harvest patterns because of different owners and management goals. Most of the LDF in the Lake Washington subbasin (0.2% of remaining LDF/decade harvested following 1992) is city- or state-owned, and is managed as a water source for Seattle; the Lower Cowlitz (3.5%/decade) is conversely largely industrial timberland.

Fire Patterns

In contrast with harvest, most LDF-clearing fire (90.7% from 1972 to 2002, Figure 5) occurred on federal land, which predominates in the region's drier southern and eastern ecosystems. Fire in LDF increased dramatically in the last decade. The impact of fire on federal LDF increased both in absolute terms (from 6,800 ha/decade from 1972 to 1992 to 45,300 ha/decade from 1992 to 2002) and in relation to the area removed by harvest (LDF area lost to fire on federal land was 1/27th the area lost to harvest before 1992 and 2.2 times greater afterward, Figure 5A). Although much of the increase in LDF lost to fire (33,700 ha) resulted from a single large fire (the Biscuit Fire of 2002), other losses of LDF still amounted to double the pre-1992 rate of LDF burning. Although increased losses to fire were, regionally, more than offset by decreased harvest (the percentage of remaining LDF lost to the combination of harvest and fire dropped from 10.7% to 7.3% per decade following the NWFP; Figure 5), increasing losses to fire were important at the local level.

Although post-NWFP fires affected only a small number of the region's subbasins, affected areas could lose as much LDF to fire as intensively managed subbasins lost to harvest. Almost all the subbasins experiencing recent increases in LDF loss to fire were located in the region's three drier provinces (Klamath and East Cascades of Washington and Oregon). In the Klamath region, the area of LDF lost to fire following 1992 was 3 times the area harvested (Figure 6B). The role of fire may be seen in the regional map of pre- and post-NWFP LDF disturbance rates (Figure 7). Although many subbasins showed declines in net LDF disturbance rates following the NWFP, large increases in the effects of fire on LDF were observed in subbasins in the southwestern (Chetco, Illinois, Smith) and the northeastern (Lake Chelan, Upper Columbia-Entiat) parts of the region. Fire was not a significant factor in LDF loss either before or after the NWFP in wetter subbasins in the western part of the region.

Discussion

The NWFP was an effort by federal forest managers across a large region to manage for specific outcomes representing a number of forest values.

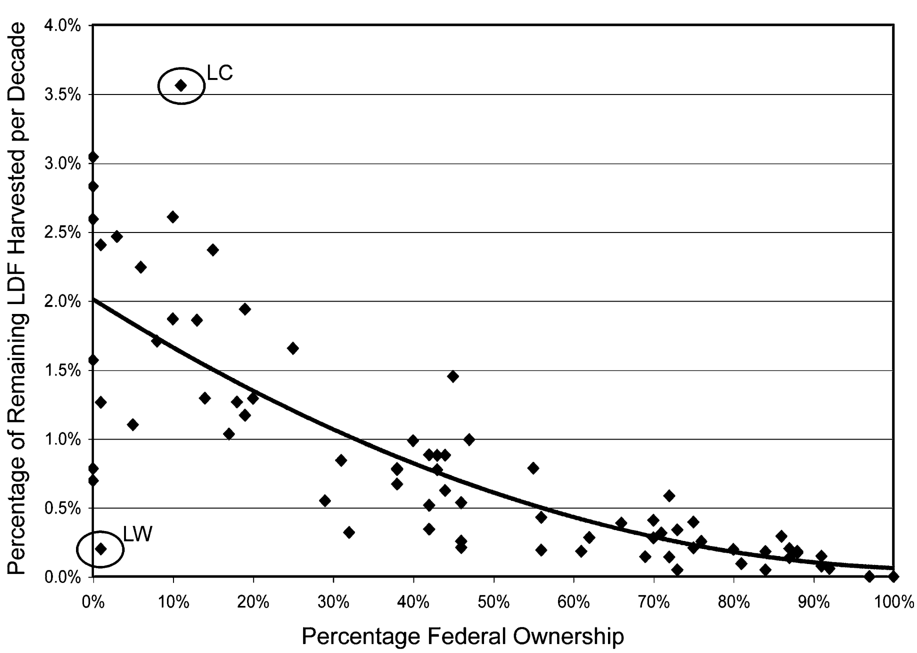

Figure 8. Relationship of federal ownership to LDF harvest following the NWFP. Although the proportion of federally owned land within a subbasin was strongly related to the level of LDF harvest ($r^2 = 0.63$; $y = 0.017x^2 - 0.037 + 0.02$), some variation occurred in subbasins with little federal land. As discussed here, the Lake Washington (LW) and Lower Cowlitz (LC) were managed differently by different mixes of non-federal owners.

Among these desired outcomes was the maintenance of a network of older forests that would be sufficient to support populations of species dependent upon such forests. This network was expected to be extensive enough to function with little contribution from non-federal lands and despite losses to wildfire and logging (Spies 2006). In the discussions about the effects of harvest and fire that follow, it is important to remember the limitations of the LDF class imposed by the nature of remote sensing and the paucity of adequately geo-referenced 1972-era field data. The available historical validation data suggested that the LDF class in 1972 corresponded roughly to conditions Strittholt and others (2006) defined as ''mature and old-growth'': that is, greater than 50 years of age. Forests with a great variety of structural conditions and ecological functions may exist in this range. In using this broad class, it is possible that trends in true old growth, the characteristics of which are not always easily measured with satellite imagery, have been obscured. Nevertheless, by focusing on losses of forests having relatively large trees in 1972, this work offers context for how coordinated forest management may or may not extend protections of older forests across a landscape. Specifically, the NWFP provides an example of how increasing rates of natural disturbance may significantly offset sweeping reductions in older forest harvests.

The Effect of Harvest on LDF

Federal owners (primarily the Forest Service and BLM) combined to harvest relatively large amounts of LDF during the 1970s and 1980s (Figures 4 and 5). Given the concentration of older forests on federal land in the region (Bolsinger and Waddell 1993; Strittholt and others 2006), the significant declines in federal harvest following the NWFP therefore had far-reaching effects on regional LDF stocks. The decline in federal harvesting under the NWFP was actually greater than had been anticipated by federal planners. Federal timber production, most of which came from partial harvests and thinning (Charnley and others 2006), amounted to only about 54% of the amount of harvest expected to be sustainable under the NWFP (that is, ''probable sale quantity'' or PSQ; Baker and others 2005). If one assumed that increasing harvest volume would lead to a proportionate rise in the rate of LDF loss, harvest of the full PSQ during the study period would have removed only an additional 17,700 ha of LDF per decade from 1993 to 2002 (0.6% of the remaining federal LDF). Conversely, continuation of peak pre-NWFP rates of LDF removal on federal lands (from 1984 to 1988) would have resulted in an additional loss of 206,000 ha between 1993 and 2002 (7.1% of the current total). Even with full implementation of the PSQ, the NWFP would still therefore represent a significant increase in the protection of older forests within the region.

The decline of federal harvesting of older forests coincided with significant growth of the area of federal LDF. Moeur and others (2005) estimated that the area of the region's non-wilderness Forest Service land in the ''medium and large'' older forest class (similar to LDF) grew by 1.9%/year in the decade following the NWFP, although most of this increase came in the lower end of the considered size range. At the same time that older forests were making significant gains on federal land, gross harvest of non-federal LDF declined significantly in the 1990s. If state and private owners had responded to the relatively abrupt cut in federal timber production by proportionally increasing harvest of their own LDF, the conservation benefits of the NWFP would have been offset by actions in other parts of the landscape. However, the maps supporting this work indicated that, particularly on lands owned by the forest industry, there simply were not enough older forests to maintain past levels of LDF harvest. Non-federal LDF harvest rates following the NWFP were actually steady when measured as a percentage of remaining forest, suggesting that absolute state and private LDF harvests might have been greater if more LDF had been available.

Spatial trends were largely dependent upon patterns of ownership. The amount of harvest in a province or subbasin following the NWFP was strongly related to its proportion of federal land (Figure 8). This agreed with results of Wimberly and Ohmann (2004), which identified ''proportion of private ownership'' as the primary predictor of loss of larger conifer forests from 1936 to 1996 in the Oregon Coast Province. There are, however, significant differences in the goals and practices of different owners in the ''non-federal'' category, and these differences were reflected in subbasin-level harvest patterns. The subbasins showing the highest variability in harvest rates in Figure 8 were those dominated by some mix of non-federal owners. Non-industrial owners often consider a range of forest values beyond market price in management decisions (Beach and others 2005), and this analysis showed that they have consistently harvested LDF less intensively than industrial owners (Figure 4). State owners in this region, although depending on timber revenues to some degree, may have significant areas of older forest in habitat conservation plans that restrict harvests options (WA DNR 2004). As was the case on non-industrial private lands, state LDF harvest rates were well below those of private industrial owners. Disparities in the harvest rates of these ownership groups have also been observed in other regions (for example, Sader and others 2006).

The majority of mapped LDF on industrial lands had been harvested by 2002, and some of what was left is protected under habitat conservation plans (for example, USFW 2006). The increasing concentration of remaining non-federal LDF on less intensively harvested state and private lands suggests that old forest conservation actions on federal lands can be supported in some cases by actions on non-federal lands. The benefits of this phenomenon would be realized in particular landscapes or watersheds where federal lands are a small part of the overall area. The NWFP did not appear to result in an increase of harvest of LDF on non-federal lands; LDF harvests declined or held steady at relatively high rates in provinces and subbasins dominated by the forest industry. The NWFP did, however, significantly reduce federal harvest of older forests, which led to net decreases in LDF harvest rates in most areas within the region. These changes, against the backdrop of supply-related slowing of non-federal LDF harvest and the large-scale maturation of federal forests reported by Moeur and others (2005), suggest significant progress in providing for older forest ecosystems throughout the region under the NWFP.

The Effects of Fire

The satellite record suggests that fire is now a much more important factor in the loss of older forests than it was when the NWFP was developed, and that for older forests in large parts of the landscape, fire has become the dominant disturbance process. Westerling and others (2006) found that the sudden increase in fire activity in the western United States since the 1980s was strongly related to higher spring and summer temperatures and earlier snowmelt. Knapp and Soulé (2007) linked higher fire activity in parts of the western US to changes in the timing and frequency of mid-latitude cyclones. Looking forward, McKenzie and others (2004) predicted that even under conservative climate change scenarios, the area of forest burned in most western states is likely to double by the end of this century. Thus, although relatively unique circumstances (including large, coordinated public ownership) may have contributed to the significant reduction of LDF harvest following the NWFP, the region's increased losses of older forests to fire may be representative of other western ecosystems, particularly if climatic conditions continue to change.

Agee (2003) suggested that, given the size of fire disturbances in this region, the subbasin scale (approximately 200,000 ha in this study area) may be too small to be considered in equilibrium with respect to damage and recovery associated with fire. It may therefore be reasonable to expect significant future losses in at least some dry subbasins unaffected by fire in the last 30 years. At the same time, fuels created by past fires may increase the likelihood that re-burns will delay the development of older forests in some subbasins (Thompson and others 2007).

The potential of fire to reduce older forest stocks independently of changes in harvest levels highlights the importance of fire management. A number of strategic fuel management approaches have been proposed that may have the potential to reduce the impact of fire on the landscape (for example, Stephens 1998; Finney 2001; Agee and Skinner 2005; Hessburg and others 2005; Spies and others 2006). The NWFP (and more recently, the Healthy Forests Restoration Act: Bill HR 1904) did acknowledge the importance of management to reduce the risk posed to older forests by fire, but in practice, fuel management programs have not been effectively coordinated across the region (Stephens and Ruth 2005). The cost of fighting increased levels of fire is one factor that has reduced federal agencies' ability to address fuel conditions in and around older forests. The US Government Accountability Office (2004) found that significant amounts of money originally allocated for fuel treatment throughout the country between 1999 and 2003 were appropriated for fire fighting.

The growing role of fire in western US ecosystems suggests that management goals related to preserving older forests may not be met solely though moderating harvest. The NWFP illustrates a case where losses of LDF have actually increased across large areas despite significantly reduced harvest levels. If fire levels continue to rise as a function of climate change, preservation of older forests in dry ecosystems will depend upon practical and coordinated fire management at the landscape level.

Conclusions

Patterns in the PNW illustrate both how harvest by an array of owners can affect the dynamics of a region's older forests and how natural disturbances can often eclipse the impact of harvest. In just

10 years (1992–2002), patterns in the loss of older forests in the PNW changed dramatically. Federal harvest of older forests, which had been significant prior to the NWFP, virtually ceased afterward, affecting the dynamics of older forests throughout the region. Federal harvests have fallen short of the probable sale quantity (PSQ) suggested under the NWFP, but our maps suggest that even full harvest of the PSQ would have represented a significant reduction in the federal LDF harvest rate relative to activities in the 1980s. The region's other main timber producer, private industrial forest owners, harvested much less older forest in the 1990s than in the preceding two decades because of declining stocks. The regional rate of harvest for non-federal older forests is expected to continue to decline because much of the remaining 1972-era LDF is on state and non-industrial private lands that, historically, have been less intensively managed than industrial forests. Meanwhile, major fire events in older forests following the NWFP exceeded the scope of previous fires in number and area. LDF losses to fire were concentrated on federal lands in the drier East Cascades and Klamath provinces, where increased disturbance by fire outweighed decreased disturbance by harvest. More comprehensive fire prevention and suppression activities may be needed on federal lands to avoid significant losses of older forests in drier parts of the region, particularly if recent climatic trends continue.

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