Ecosystems (2002) 5: 122–137
DOI: 10.1007/s10021-001-0060-X

ECOSYSTEMS

ORIGINAL ARTICLES

Characterizing 23 Years (1972–95) of Stand Replacement Disturbance in Western Oregon Forests with Landsat Imagery

Warren B. Cohen,[1]* Thomas A. Spies,[1] Ralph J. Alig,[1] Douglas R. Oetter,[2] Thomas K. Maiersperger,[2] and Maria Fiorella[2]

[1]Forestry Sciences Laboratory, Pacific Northwest Research Station, USDA Forest Service, 3200 SW Jefferson Way, Corvallis, Oregon 97331, USA; and [2]Department of Forest Science, Forestry Sciences Laboratory 020, Oregon State University, Corvallis, Oregon 97331, USA

ABSTRACT

In western Oregon, forest ecosystem processes are greatly affected by patterns of stand replacement disturbance. A spatially explicit characterization of clear-cut logging and wildfire is a prerequisite to understanding the causes and consequences of disturbance in this region. We analyzed stand replacement disturbance over 4.6 million forested hectares of three major provinces in western Oregon between 1972 and 1995, contrasting the relative amounts of wildfire and harvest in each province and comparing harvest statistics among the dominant land ownership categories. Clear-cut harvest and wildfire occurred over 19.9% and 0.7% of the study area, respectively. The moist Coast Range Province (CRP) was dominated by private industrial (PI) ownerships and had the greatest concentration of cutting. The relatively dry Klamath Mountains Province (KMP) and the climatically moderate Western Cascades Province (WCP) were dominated by public landowners and had lower concentrations of cutting and larger amounts of wildfire than the CRP. Rates of harvest over time generally followed similar trends across landowners; it was lowest in the early 1970s, peaked in the late 1980s and early 1990s, and then decreased to near 1970s levels by the mid-1990s. PI landowners had harvest rates that were about two and one-half times as high as public owners throughout the study period. Public and private nonindustrial (PNI) owners tended to have relatively small cutting units that remained spatially dispersed throughout the study period, whereas the PI owners had larger individual cutting units that tended toward spatial aggregation over time. Comparing the managed disturbance regimes with historical wild disturbance regimes can help us to understand the relative impact of management regimes on ecosystems.

Key words: forest disturbance; Landsat; forest management; remote sensing; change detection; province; ownership.

INTRODUCTION

Regional forest dynamics influence a variety of ecosystem functions, including terrestrial and aquatic species habitat (Harris and Silva-Lopez 1992; Csuti and others 1997), water quality and flows (Saunders and others 1991), and the carbon cycle (Houghton 1993; Cohen and others 1996). Although some regions of the Earth have experienced a net increase in forest area over the past 100 or more years due to the abandonment of marginally

Received 28 November 2000; accepted 24 September 2001.
**Corresponding author; e-mail:* warren.cohen@orst.edu

productive agricultural sites (Waddell and others 1989; Kauppi and others 1992), many regions have undergone a net loss in forest area, such as the tropics (Green and Sussman 1990; Skole and others 1994) and much of the western United States (Alig and Wear 1992; Bolsinger and Waddell 1993). Although ground-based forest inventories are important for monitoring forest change (Waddell and others 1989), they cannot provide the spatial characterization of change that is needed for the assessment of habitat fragmentation and its effects on the watershed. Moreover, in many regions of the Earth, there are no—or scant—ground-based forest inventory data.

Since 1972, it has been possible to monitor forest resources using satellite imagery (Goward and Williams 1997). Global vegetation maps have been derived from Advanced Very High Resolution Radiometer (AVHRR) data (Defries and Townshend 1994; Prince and Goward 1995; Belward and others 1999); and with the recent launch of the Moderate Resolution Imaging Spectrometer (MODIS) sensor, mapping of global forest resources is becoming routine (Running and others 1999). Because they are designed for global mapping, both of these satellite sensors have a coarse ground resolution, or grain size (approximately 1 km)—a spatial resolution that is generally too coarse for monitoring localized or regional forest management activities. Regional mapping of forest cover has primarily relied on finely resolved data, such as 30-m Landsat Thematic Mapper (TM) (Vogelmann and others 1998; Cohen and others 2001). Cover mapping of the same area repeated at least once permits evaluation of forest-cover change (Hall and others 1991) using a process that is termed "delta classification" (Coppin and Bauer 1996), or, more commonly, "post-classification comparison." An alternative means of monitoring forest-cover change involves analyzing image spectral changes over time (Collins and Woodcock 1994). This approach is likely more accurate because it avoids the compounding of errors that arise when two separate maps are compared, as occurs when the delta classification approach is used (Coppin and Bauer 1996).

Monitoring of both forest disturbance and succession is possible with satellite-image data (Foody and others 1996; Rignot and others 1997). However, disturbances that do not result in stand replacement (such as thinning) and successional processes that involve slowly changing species composition or competitive self-thinning can be difficult to characterize accurately. In contrast, stand replacement disturbances (for example, wildfire, clear-cut logging, windthrow) tend to be demarcated in time as large visible events and can therefore be mapped more readily using image data.

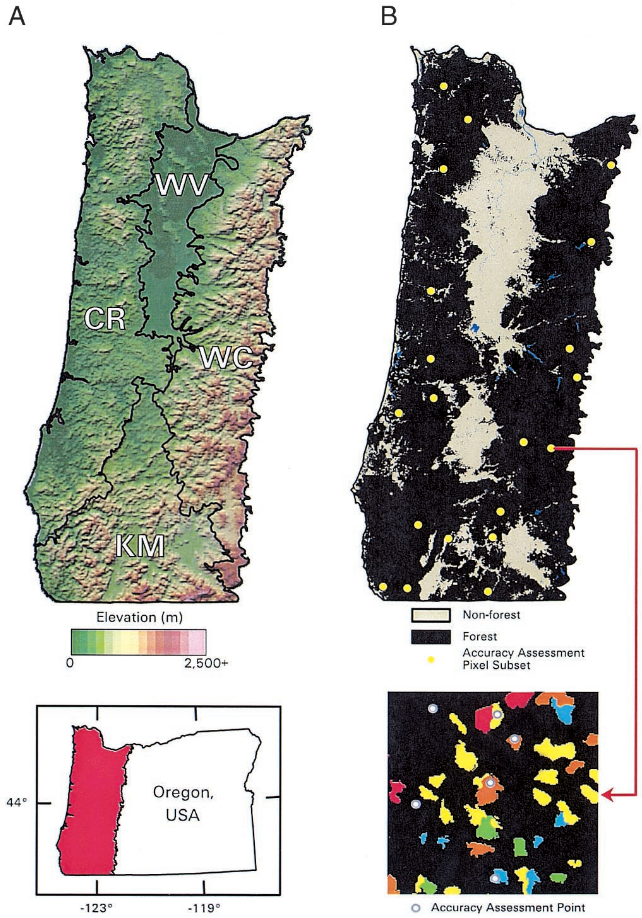

Figure 1. Study area in western Oregon, showing (**A**) elevation and geoclimatic provinces (CR = Coast Ranges, WC = Western Cascades, KM = Klamath Mountains, WV = Willamette Valley), (**B**) forest versus nonforest and location of accuracy assessment pixel subsets, and **C** an enlargement of a portion of one subset showing the location of accuracy assessment points. The province boundaries are adapted from USDI (1998). Determination of forest vs nonforest was derived from the Oregon State Service Center for GIS, Generalize Zoning Coverage for Oregon (ftp://ftp.sscgis.state.or.us/pub/data/statewide/k100/zoning.html). The key for the colors used in the enlarged subset section is given in Fig. 3.

Local to regional monitoring of forest disturbance using satellite imagery has largely focused on the derivation of methods (Sader and Winne 1992; Cohen and others 1998). Although some studies have focused on the impact of disturbance patterns on habitat (Spies and others 1994; Radeloff and others 2000), biodiversity (Ripple and others 1991), and carbon flux (Cohen and others 1996), these studies were conducted over relatively small spatial ex-

Table 1. Forest Area (ha) by Owner and Province

Owner	Coast Range	Western Cascades	Klamath Mountains	Total
Private nonindustrial	292,149	122,921	137,544	552,614
Private industrial	663,669	365,119	145,952	1,174,740
State of Oregon	244,344	19,450	6,348	270,142
Bureau of Land Management	285,721	168,394	311,466	765,580
Forest Service	272,290	1,062,861	355,516	1,690,667
Other	24,492	60,342	26,878	111,712
Total	1,782,665	1,799,087	983,704	4,565,455

tents. In this study, we characterize the relationships among disturbance rates and patterns, geoclimatic gradients, and land ownership to determine the impact of land management activities and wildfire across the 4.6 million forested hectares of the three major forest provinces in western Oregon between 1972 and 1995. Our objectives were to:

1. Characterize the rate and distribution of stand replacement disturbance;

2. Contrast the relative importance of wildfire and clear-cut harvest as forest disturbance agents; and

3. Compare rates and patch size distributions of forest cutting units among the major land ownership categories and geoclimatic provinces.

Methods

Study Area

Western Oregon is a topographically complex area (Figure 1) that, outside the major valley systems, is predominantly covered with forest vegetation (Cohen and others 2001). Franklin and Dyrness (1988) provide the most comprehensive ecological and climatic description of the area, which is among the more diverse regions of North America in its environment and vegetation. The physiographic and geographic provinces included in this study are the Coast Ranges (CRP), the Western Cascades (WCP), and the Klamath Mountains (KMP) (Figure 1). The Willamette Valley Province is primarily agricultural and therefore is not discussed in this study. Climatically, the study area varies greatly, with annual precipitation ranging from as low as 60 cm in the eastern portion of the KMP to over 300 cm in the northern CRP. Mean monthly minimum temperatures range from –5°C in the eastern parts of the WCP and KMP to 5°C in the western part of the KMP. Mean monthly maximum temperatures range from 31°C in the southern KMP to 20°C along the coast from the northern CRP to the southern KMP. The KMP is the most climatically diverse portion of the study region. These forested provinces also differ in fire and management history, which has created additional diversity in canopy structure.

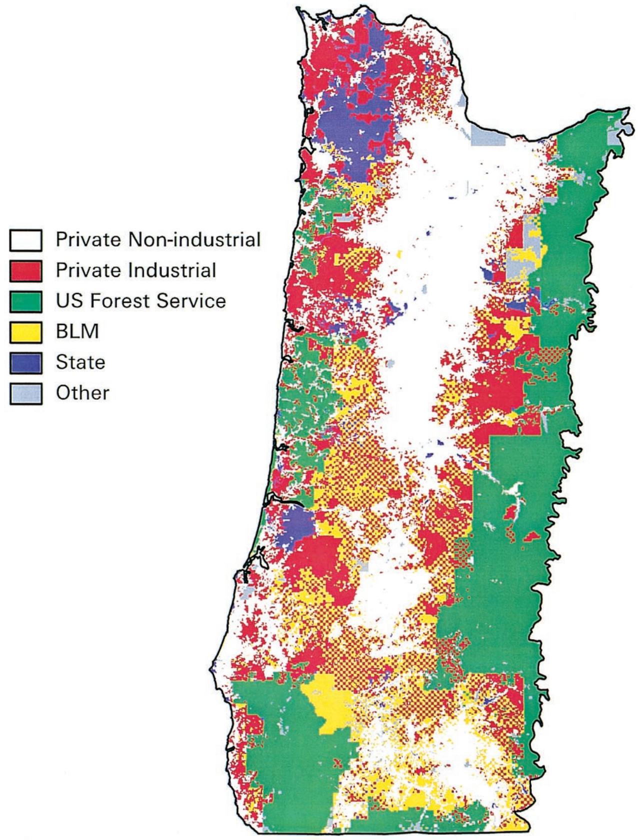

Figure 2. Ownership categories across the study area as derived from the Corvallis Forestry Sciences Laboratory, Western Oregon Industrial Forest Land Ownership GIS Layer (ftp://ftp.sscgis.state.or.us/pub/data/statewide/k24/worfrst.txt). BLM = Bureau of Land Management.

There are several different major forest vegetation zones in the study area (Franklin and Dyrness 1988). The Sitka Spruce Zone is only a few kilometers in width and occurs along the full length of the Oregon coast. The Western Hemlock Zone is the most extensive vegetation zone in the study area and has two major segments: the majority of both the CRP and the WCP. The Mixed Conifer/Mixed Evergreen Zone occurs primarily in the KMP; the Subalpine Forest Zone occurs in the high elevation portion of the WCP; and in the far southeast part of the study area is a small portion of the Ponderosa Pine Zone. Across these forest zones, 22 coniferous tree species in nine different genera and numerous hardwood tree species in several major genera are represented. Dominant trees are typically conifers, except in riparian areas and dry valley margins, where hardwood trees can dominate.

The study area consists of 4.6 million forested hectares (Table 1). Of the total area, 39% is in the CRP, 39% is in the WCP, and 22% is in the KMP. Sixty percent of the area is managed by public agencies—37% by the United States Department of Agricuture (USDA) Forest Service (FS), 17% by the United States Department of the Interior (USDI) Bureau of Land Management (BLM), and 6% by the state of Oregon (SO). The private industrial (PI) and private nonindustrial (PNI) owners make up the bulk of the remaining ownership, at 26% and about 12%, respectively. Two percent of the area is distributed among a variety of miscellaneous owners (Other), including, for example, tribal and county lands.

Ownership patterns are variable by province (Figures 1 and 2, Table 1). Within the CRP, PI ownership dominates (37%), with a nearly equal distribution among remaining categories (except for Other). In the WCP and KMP, the FS is the dominant owner (59% and 36%, respectively). In the WCP, another important ownership group is the PI (20%); all remaining categories control less than 10%. In the KMP, the BLM controls an extent of land nearly equal to the FS (32% and 36%, respectively), whereas the PI group owns about half as much as each of the two federal agencies. The only province in which the SO owns a sizeable portion of land (14%) is the CRP.

Within the public ownerships, there are several land-use designations that restrict or prohibit clearcutting, including wilderness, Research Natural Area, National Park, scenic areas, and sensitive habitat designations. Protected areas have been added continually since the 1970s. As such, most—but not all—protected areas were identified in our circa mid- to late-1980s ownership data layer. In the CRP at that time, 7.0% of the holdings in the FS ownership category were protected land. In Other category (USDI Fisheries and Wildlife Service), 0.3% of the holdings were protected land in the CRP. In the WCP, 9.1% of the holdings of the FS were protected land, and 2.8% of the lands in the Other category (USDI National Park Service) were protected. In the KMP, 21.5% of the FS holdings and 1.0% of the BLM holdings had protected status. An extensive reserve network for late-successional habitats and watersheds on federal lands was initiated in 1994 and 1995 (FEMAT 1993), but it had relatively little impact on the dynamics observed in this study.

Image Data and Preprocessing

The images used in this study are all from the Landsat satellite; the earlier dates are from the Multispectral Scanner (MSS) sensor and the latter are from the TM sensor (Appendix). Following Cohen and others (1998), each individual MSS and TM image was transformed into Tasseled Cap brightness and greenness vegetation indexes (Kauth and Thomas 1976; Crist and Cicone 1984). These indexes compress the original, highly correlated spectral bands into a smaller set of indexes that are physically interpretable in relation to regional forest properties (Cohen and others 1995). The additional bands of data from the shortwave infrared portion of the electromagnetic spectrum available in TM data permitted the use of an additionally important physically interpretable index known as "wetness" (Crist and Cicone 1984; Collins and Woodcock 1994), for a total of 15 spectral bands.

The 1988 data was georeferenced to UTM Zone 10, NAD 27, at a pixel resolution of 25 m. A mosaic of 1988 images was developed; all images from the other dates were georeferenced to this mosaic. A minimum of 30 ground control points per full image were selected and first- and second-order nearest neighbor resampling was performed, with resulting pixel sizes of 25 m and root mean square errors of generally less than one pixel. To assemble the mosaics of imagery for all other time periods, as for the 1988 mosaic, we based image dominance in the overlap region among neighboring images on relative image quality.

There were radiometric differences among the images in both space and time, but the noise associated with temporal radiometric differences is minimal relative to the signal from stand replacement forest disturbance (Cohen and others 1998). Thus, it was not necessary to perform radiometric normalization, as is generally recommended (Coppin and Bauer 1996). However, to further reduce the high volume of data contained within the full six-date spatial and temporal mosaic (and thus the difficulty in processing and handling) and to avoid the inclusion of both "spatial" and "temporal" radiometric differences in subsequent analyses, we chose to spatially segment the mosaic. Due to the two different Path/Row structures of the MSS and TM data and additional problems associated with partial cover of cloud, the number of spatial segments for the temporal mosaic was 21.

Disturbance Detection

This study follows a prototype disturbance detection exercise reported by Cohen and others (1998) and a conceptual examination of change detection algorithms by Cohen and Fiorella (1998). For the current study, we combined the knowledge gained in these early studies by conducting (on each of the 21 spatial segments) an unsupervised classification on the full stack of 15 Tasseled Cap indexes. Unsupervised clustering was an iterative process whereby individual image pixels were labeled as "disturbed" (by time period), "undisturbed," or "confused." "Confused" pixels were reclustered several times until all pixels could be confidently labeled as "disturbed" or "undisturbed." The 21 spatial segments were mosaicked after all were classified.

The mosaicked disturbance map was subjected to three processes for further refinement. The first was to relabel all nonforest land-use areas as nonforest, using a zoning data layer available through the Oregon State Services Center for GIS (Figure 1). The second process was to "smooth" all patches within the forest class (both disturbed and undisturbed) using a 3 × 3 majority filter and then merge all patches less than 2 ha with surrounding patches that were larger than 2 ha. The rule set used allowed all patches of forest disturbed during different time intervals to be merged prior to any mergers of disturbed and undisturbed forest. Third, to distinguish between clear-cut harvest and wildfire, the full disturbance mosaic was carefully viewed, and polygons representing burns were labeled "fire" and all other polygons were labeled "harvest." Burned polygons were distinguished from clear-cut ones by size, shape, and distribution, and corroboration with recent historical information on fires.

Accuracy Assessment

Cohen and others (1998) evaluated three methods of characterizing errors in a map of stand replacement disturbance in western Oregon: map comparisons with (a) an independent digital polygon database from a major land management agency, (b) a visual patch-level interpretation of the original Landsat imagery, and (c) a visual pixel-level interpretation of the original Landsat imagery. All of these yielded nearly identical results. Because the visual pixel-level interpretation is the easiest to perform and the least spatially biased, that method was chosen for the current study.

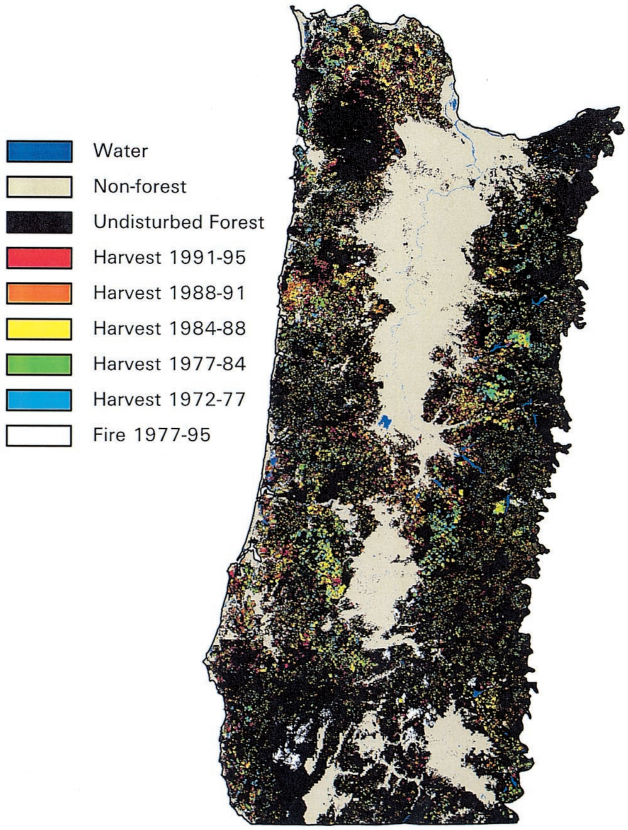

Figure 3. Stand replacement disturbance map.

Accuracy assessment commenced with a random selection of 20 "center points" among the three forested provinces of the disturbance map (Figure 1). For each center point, we extracted a 512 × 512 pixel subset (12.8 × 12.8 km) of the disturbance map with the selected point at the center. Each subset had to meet the minimum requirement of being at least 75% forest land use, and each of the observed disturbance classes had to be represented in at least one subset. For each of these 20 subsets, we randomly selected 40 accuracy assessment points (that is, pixels), where a maximum of 60% could be from the undisturbed or nonforest classes. If a selected point was from a disturbed class, it was kept only if no other point fell within the same disturbance patch, where a patch was defined as a spatially connected group of pixels disturbed in a single time period by the same agent (fire or harvest) (Figure 1). All selected pixels within the classes mapped as undisturbed forest were geo-

Table 2. Disturbance Map Error Matrix

		Observed										
		Harvest					Fire					
Predicted	Undisturbed	1991–95	1988–91	1984–88	1977–84	1972–77	1991–95	1988–91	1984–88	1977–84	1972–77	Total
Undisturbed	301	1	5	9	11	11	2	0	1	1	0	342
Harvest 1991–95	10	51	0	0	0	0	0	0	0	0	0	61
Harvest 1988–91	2	0	40	0	1	2	0	1	0	0	0	46
Harvest 1984–88	5	0	1	62	1	1	0	0	0	0	0	70
Harvest 1977–84	2	0	0	3	71	3	0	0	0	1	0	80
Harvest 1972–77	2	0	0	0	3	38	0	0	0	0	2	45
Fire 1991–95	1	0	0	0	0	0	9	0	0	0	0	10
Fire 1988–91	0	0	0	0	0	0	0	10	0	0	0	10
Fire 1984–88	2	0	0	0	0	0	0	0	10	0	0	12
Fire 1977–84	0	0	0	0	0	0	0	0	0	11	0	11
Total	325	52	46	74	87	55	11	11	11	13	2	687
Proportion correct	0.926	0.981	0.870	0.838	0.816	0.691	0.818	0.909	0.909	0.846	0.000	0.878

Table 3. Harvest Area (ha) by Owner and Province

Owner	Coast Range	Western Cascades	Klamath Mountains	Total
Private nonindustrial	67,219	16,931	13,156	97,306
Private industrial	297,091	132,158	33,287	462,536
State of Oregon	29,747	2,095	593	32,435
Bureau of Land Management	46,987	28,692	30,781	106,460
Forest Service	33,315	138,004	20,856	192,175
Other	6,010	10,446	2,027	18,483
Total	480,369	328,326	100,700	909,395

Table 4. Burn Area (ha) by Owner and Province

Owner	Coast Range	Western Cascades	Klamath Mountains	Total
Private nonindustrial	0	4	763	767
Private industrial	1,005	975	3,809	5,790
State of Oregon	0	0	241	241
Bureau of Land Management	123	691	7,190	8,004
Forest Service	0	1,158	15,224	16,382
Other	0	5	116	121
Total	1,128	2,833	27,343	31,305

graphically redistributed to maximize the separation among points within the subset area, thereby minimizing pseudoreplication by reducing the likelihood that multiple points were from the same, undisturbed forest stand. Of the possible 800 points, 113 were from the nonforest class and were not further assessed, leaving 687 points to assess for accuracy. Each of the 687 accuracy assessment points was evaluated by loading each of six image-viewing windows opened on a computer monitor with one of the six dates of original Tasseled Cap–transformed imagery. With all image viewers "geographically linked," every accuracy assessment point was viewed in each date of imagery and a determination was made as to whether a point was disturbed, and if so, when. Point-level determinations were necessarily made in the context of the apparent fate of neighboring pixels, but without reference to the disturbance map. After we visually noted the fate of all sampled pixels (undisturbed or disturbed by fire or harvest and time interval of disturbance), the visual calls (or labels) were compared to their corresponding disturbance map labels to construct an error matrix. We then compared the summary statistics with the available clear-cut harvest data for the region.

Summary Statistics

The stand replacement disturbance map was summarized to obtain statistics on (a) the percent of forest clear-cut harvested versus the percent burned, (b) harvest rates over the study period, and (c) individual harvest and burn unit sizes versus aggregated harvest and burn unit sizes. These statistics were stratified by ecoregion (Figure 1) and ownership category (Figure 2). An individual disturbance unit consists of spatially contiguous pixels of a given disturbance type (that is, harvest or burn) that were disturbed in a given time interval. "Aggregation," as used here, refers to the spatial agglomeration of contiguous units disturbed at different time periods.

Results

Stand Replacement Disturbance Map

The stand replacement disturbance map (Figure 3) reveals patterns of disturbance associated with both geoclimatic province (Figure 1) and ownership (Figure 2). Overall, the CRP was the most greatly disturbed, followed by the WCP and the KMP. Harvest was the dominant disturbance

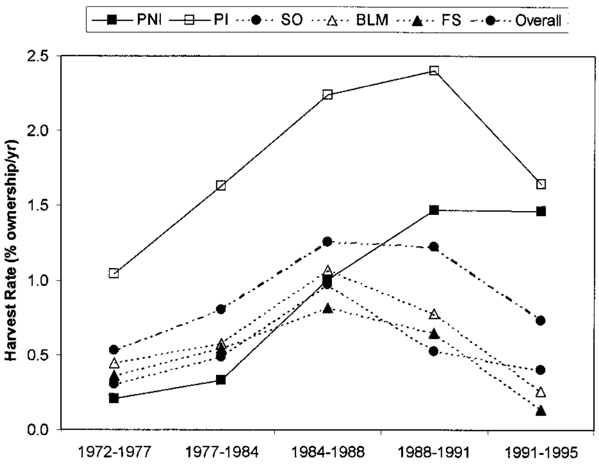

Figure 4. Harvest rates over time by ownership category.

agent in all three provinces. Although fires occurred in all three provinces, they were most numerous in the KMP and were largely confined to wilderness areas. Across all provinces, the largest concentrations of cutting occurred in the PI ownership category, which mostly occupies large blocks of land at the lower elevations of the study area. Over time, the PI cutting units tended to be spatially aggregated. For the FS ownership, there was a strong tendency toward the dispersion of individual cuts. For BLM lands, which exist mostly in small ownership blocks interspersed with PI lands, the cutting pattern was also dispersed. Some landscapes within the region experienced little or no cutting during the study period, especially SO lands in the northern CRP and the federal wilderness areas in the KMP and along the eastern margin of the WCP.

Overall, the accuracy of the stand replacement disturbance map was 88% (Table 2). Most of the mapping errors were associated with disturbance intervals that involved at least one date of MSS data (1984 and earlier) (see Appendix). For the first time interval, 20% (11 of 55) of harvest was mapped as undisturbed. For the second and third periods, respectively, 13% and 12% of harvest was mapped as undisturbed. Interestingly, 16% of lands mapped as harvested in the 1991–95 period were observed as undisturbed. Overall, of the 314 harvest observations, 12% were mapped as undisturbed. No harvested lands were mapped as fire, but 8% of burned land was predicted as harvested and 6% was predicted as undisturbed. Of the total number of undisturbed observations, 7% were mapped as disturbed. Contrasting this with the 12% of disturbed land being mapped as undisturbed, there was an overall 5% underprediction of disturbance. These error rates and biases are consistent with the results from our earlier study (Cohen and others 1998).

Summary Disturbance Statistics

Across the forestland within the study area, almost 20% was clear-cut harvested (compare Tables 1 and 3) and less than 1% was burned (compare Tables 1 and 4). Nearly 53% of all harvest activity occurred in the CRP, with 36% occurring in the WCP and 11% in the KMP. Over the 23-year period of this study, approximately 27% of the CRP, 18% of the WCP, and 10% of the KMP were clear-cut. Of the total burned area, over 87% was in the KMP, with just over 9% in the WCP and 4% in the CRP.

Of the total harvested area, 62% occurred on private land—51% on PI and 11% on PNI holding (Table 3). For publically owned lands, 21% of the harvest occurred on FS, 12% on BLM, and 5% on SO and other holdings. Public holdings had the lowest proportion of harvested area (compare Tables 1 and 3), with between 11% and 14% of total ownership harvested by all three agencies; whereas 39% of PI and 18% of PNI holdings were cut. Nearly 17% of the Other ownership category was harvested. Of the total burn area, 52% occurred on FS, 26% on BLM, 19% on PI, 2% on PNI, and nearly zero occurred on SO and Other land holdings (Table 4).

Across ownerships, the overall rate of stand replacement disturbance was lowest in the early 1970s, at 0.5% per year of all forest land, increasing to over 1.2% per year throughout the mid-late 1980s; it then declined to 0.7% per year in the first half of the 1990s (Figure 4). Harvest rates for the PI category were consistently about twice the average rate throughout the study period, reaching 2.4% per year of total holdings in the late 1980s to early 1990s. The public holdings (FS, BLM, and SO) were harvested at a rate that was consistently below the average rate throughout the study period, the FS and SO generally having the lowest rates. Interestingly, although the PNI category had the lowest rates of harvest (0.2% per year) in the early 1970s, it ended the study period at rates nearly as high as the PI category. Although an increase in harvest rates occurred on all ownerships from the early 1970s through the mid-1980s, as the public holdings experienced reduced harvest rates in the 1988–91 period, the private holdings continued to experience increased rates throughout this period. Whereas the PI category experienced sharply reduced harvest rates in the first half of the 1990s, the

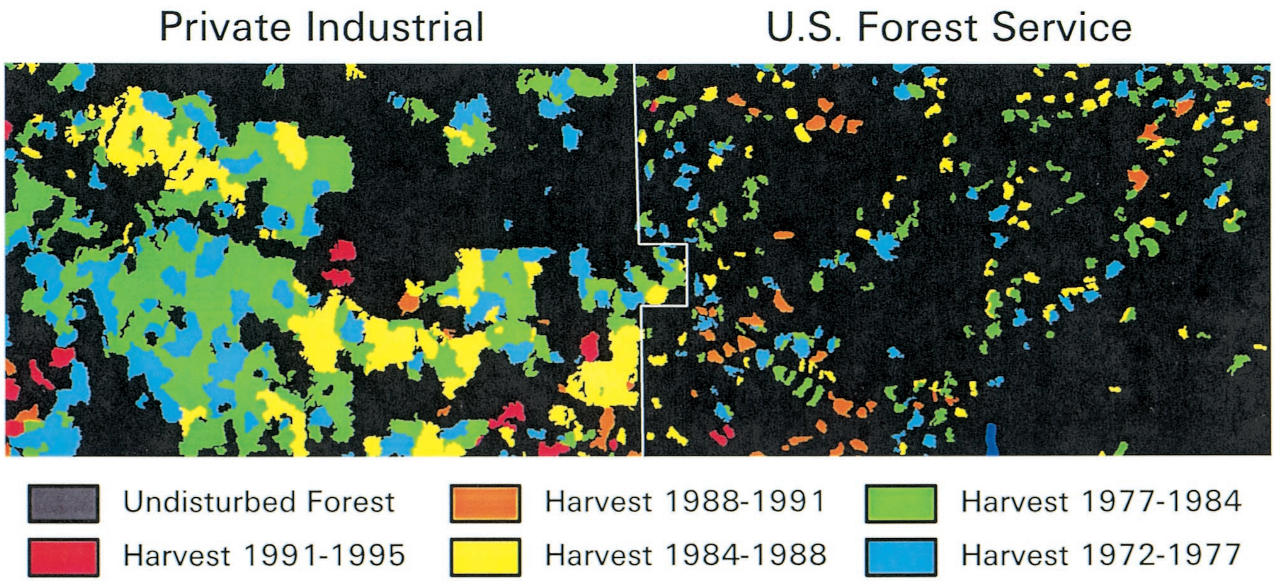

Figure 5. Example of a typical difference in clear-cut harvest patterns between private industrial owners and the USDA Forest Service in the Western Cascades.

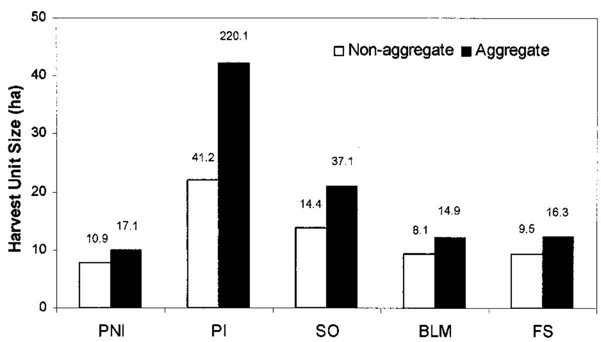

Figure 6. Harvest unit size and aggregated harvest unit sizes by ownership category. Standard deviations of units sizes are shown over bars.

PNI category maintained the same rates over the last two periods.

The mean rate of harvest for a given owner or across a given province over the 23-year period of this study provides insight into the "clear-cut return interval" for each owner or province, as reflected in recent historical terms. This is similar but not equivalent to the term "forest rotation," which is used to define the length of time a forest stand is permitted to grow before reaching maturity and thus being harvested; this term is commonly used in association with even-aged management (Davis 1966). In this region, the private landowners had the shortest clear-cut return intervals—58 years for the PI and 131 years for the PNI (calculated as the inverse of the mean annual harvest rate per owner category over the study period) (Table 3). All public holding had clear-cut return intervals between 165 years (BLM) and 202 years (FS). Note that these results are for patches 2 ha or larger and do not include units that were partially harvested. However, wilderness areas were included in the calculation of clear-cut return intervals.

By province, clear-cut return intervals were variable, with the CRP at 85 years, the WCP at 126 years, and the KMP at about 225 years (calculated as the inverse of the mean annual harvest rate per province over the study period) (Tables 1 and 3). In contrast to clear-cut return intervals by province, fire return intervals (calculated as the inverse of the mean annual burn rate per province over the study period) (Tables 1 and 4) over the 23-year period of this study were 36,349 years, 14,601 years, and 827 years, respectively, for the CRP, WCP, and KMP.

The ratio of the harvest area to the burn area was highly variable by both province and ownership (compare Tables 3 and 4). The CRP was primarily a harvest-dominated system; it had about 426 times the amount of harvested area as burned area. The amount of forest harvested on the WCP was 116 times that of burned area; and on the KMP, there was less than four times the harvest area relative to burned area. The harvest amount was 135 times the amount of burn on SO lands, whereas the harvest area was only 13 times and 12 times the burned area on BLM and FS lands, respectively. The private owners had 127 (PNI) and 80 (PI) times as much harvest as burned area.

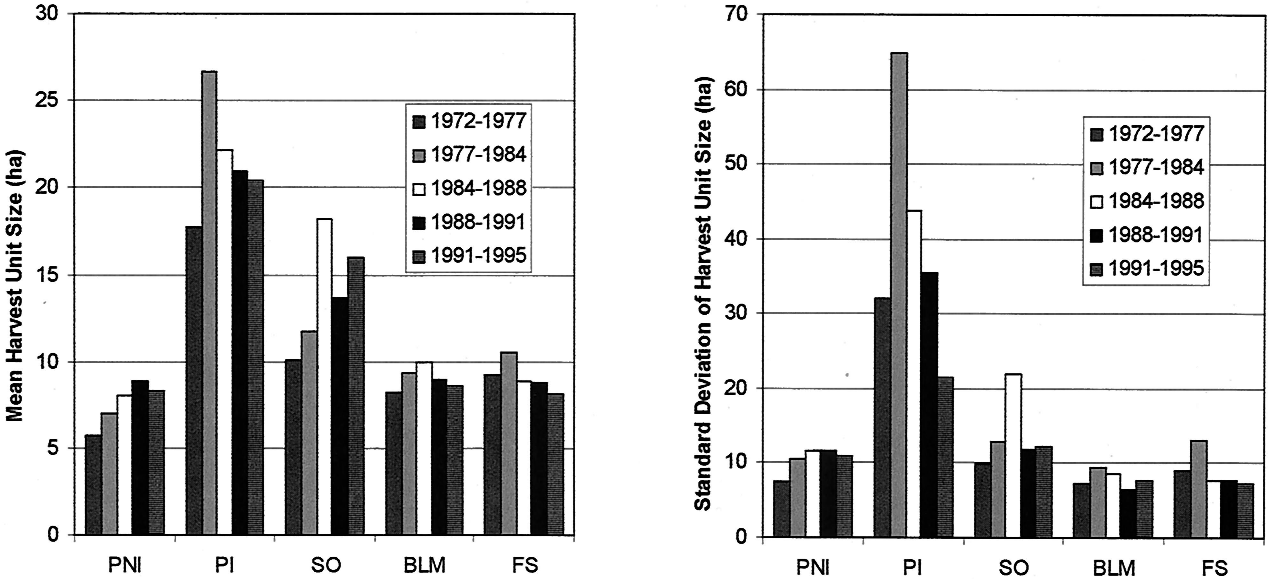

Figure 7. Mean and variability of harvest unit sizes by time period and ownership.

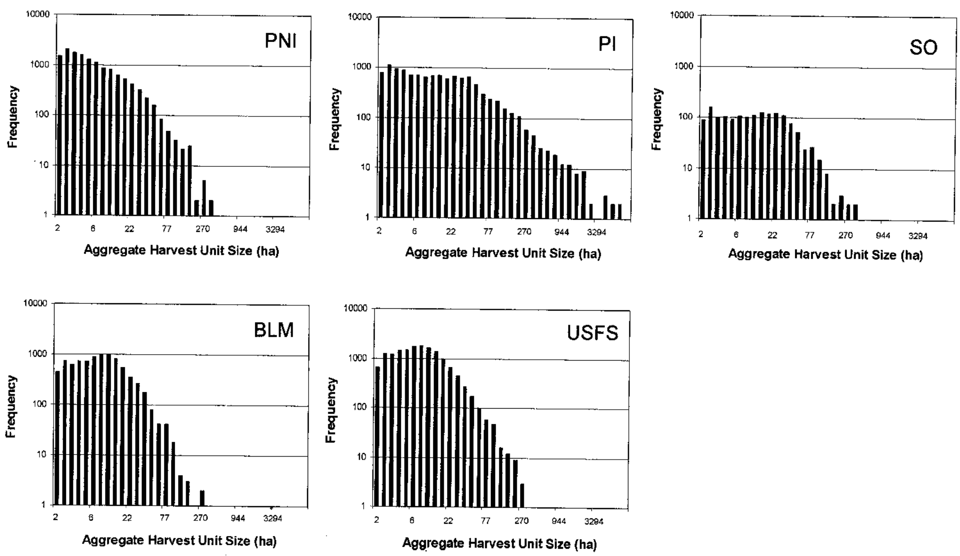

Figure 8. Frequency distributions of aggregate harvest unit sizes by ownership (log-log plot).

Harvest unit sizes were highly variable among owner categories. For example, PI lands tended to have larger individual clear-cuts relative to FS lands (Figure 5). Furthermore, the PI category was more likely to spatially aggregate clear-cuts from different time periods (Figure 5). A summary of the disturbance map across the full study area reveals that the PNI category had the lowest mean harvest unit size (nearly 8 ha), whereas the PI category had the highest unit size (about 22 ha) (Figure 6). Public holdings had mean harvest unit sizes of between 9 and 13 ha. Variability in harvest unit sizes also differed by ownership; the greatest standard deviations of unit size were associated with the PI category (41 ha), and the lowest were associated with the BLM, FS, and PNI categories (all less than 11 ha).

During the 1980s and 1990s, the PI, FS, and BLM ownerships tended toward somewhat smaller individual harvest units (Figure 7). For SO and PNI lands, there was a tendency toward larger cutting units over time. Except for SO lands, trends in the variability of harvest unit size over time were similar to trends in the mean unit

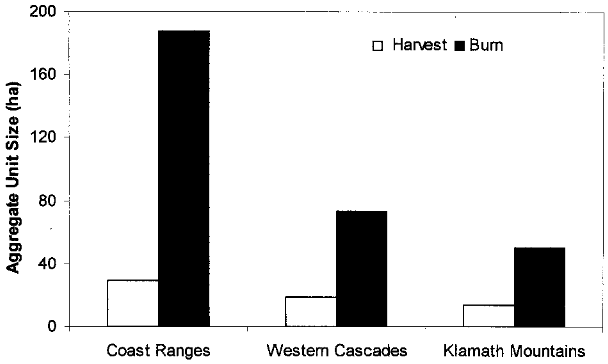

Figure 9. Aggregated harvest and burn unit sizes by geoclimatic province.

size, especially for the PI and FS owners (Figure 7). Of particular note is the two-thirds reduction in unit size standard deviation (from 65 ha down to 22 ha) on the PI lands and the nearly one-half reduction on the FS lands (from 13 ha down to 7 ha). The PNI, BLM, and state lands are generally in smaller blocks than FS and PI lands, which may have influenced the variability in size of cutting units.

Comparing aggregate harvest unit sizes with nonaggregate unit sizes, we see that all owners tended toward some level of aggregation (Figure 6). The PI category showed the greatest tendency; aggregated units were, on average, nearly twice the size of nonaggregated units. For the BLM and FS holding, this number is closer to 1.3 times. The real story in terms of aggregation is in the variability among aggregated unit sizes; PI owners had a standard deviation in aggregated unit size of over 220 ha, and all other owner categories had considerably less deviation in aggregated unit size (less than 40 ha). The largest aggregate harvest unit sizes were about 300 ha on USFS and BLM lands, 400 ha on PNI and SO lands, and as large as 9000 ha on PI lands (Figure 8).

Examining harvest unit aggregation over time by province, we see that the CRP had mean aggregated harvest units of nearly 30 ha (Figure 9). Aggregated unit sizes for the WCP and KMP were considerably smaller—less than 20 ha and less than 15 ha, respectively. Average aggregated burn unit sizes were larger than aggregated harvest unit sizes on all provinces (Figure 9). The CRP tended to have the largest burn units (190 ha), whereas the WCP and the KMP had burn units that averaged 70 ha and 50 ha, respectively.

Discussion

Comparisons with Related Studies

Our disturbance results are based almost exclusively on an analysis of satellite imagery. Given the remote nature of these observations, independent confirmation or corroboration is important. Although there are no existing databases to use in corroborating the full suite of characteristics mapped in this study, there is nonetheless some comparable information available. Zheng and Alig (1999) provide summary harvest statistics from forest inventory data for the PI and PNI ownership categories over essentially the same study area. They found that over the same time period (1972–95), the PI category had harvested 26% of its land base in western Oregon. By comparison, we found that this same ownership category harvested 39% of its total land base. Similarly, they report that the PNI category harvested 16% of its land base, as compared to our finding of 18%. The Oregon Department of Forestry (ODF) (Lettman and others 1991) records the volume of merchantable wood harvested from forests in the state, as derived from log scaling. They report that 48% of the total volume harvested between 1972 and 1995 in western Oregon came from PI lands and that 6% came from PNI lands. In this study, we found that 51% of the total area harvested was on PI lands and that 11% was on PNI lands. ODF reports that 28% and 18% of the volume harvested came from FS and other public lands, respectively, as compared to our finding that 21% and 17% of the total area harvested came from these ownership categories.

Annual averages for clear-cut probabilities for the PNI ownership category were about 0.8% over the 1972–95 study period. This is the same annual rate of final harvest by PNI owners of timberland in western Oregon reported by Zheng and Alig (1999) for the last several decades.

Temporal Harvest Trends

Trends in timber harvests differ notably both among ownerships and over time. One reason is the change in timber demand, supply, and price over the 23-year period of this study. Both PI and PNI harvest rates climbed to peaks in the 1988–91 period, as Douglas-fir prices rose from around $118 per thousand board feet during depressed timber demand conditions of the early 1980s up to around $466 during the 1988–91 period (Warren 1999). PI harvest rates peaked at an annual rate of 2.4% in 1988–91; likewise, the PNI harvest peaked at over

1.5%. In contrast, public timber sales are less influenced by price signals in timber markets, and FS and BLM harvest rates declined after the 1984–88 period. Total amount of timber harvest volume in western Oregon declined by 40% between the 1984–88 and 1991–95 periods, as the relatively large reduction in such public timber harvests contributed to the notable increase in timber prices in the early 1990s. Timber prices have decreased since the peaks of the early 1990s, and PI and PNI harvest rates either fell or leveled off during the last measurement period in this study.

Private timberlands now provide the vast bulk of the timber harvest in western Oregon. In 1995, private timberlands were the source of 85% of total timber harvest. In contrast, National Forests provided 6% of the total, as compared to 34% in 1980. This notable shift over time in harvest shares among ownership categories is related to the revised role of reserved public lands under the Northwest Forest Plan (FEMAT 1993). At the same time, the higher timber prices from reduced public timber harvests has provided incentives to private owners to alter their land management plans, including going to shorter timber rotations in some cases.

Partial Harvesting

As utilized in this study, remote sensing could not ascertain the extent or frequency of partial harvesting, defined as a type of harvest that does not remove all merchantable trees. Partial harvesting in the region of this study is important; ground surveys have found that partial harvesting was more frequent than clear-cutting on PNI lands for the Douglas-fir and red alder cover types (Alig and others 2000). Clear-cut return intervals imputed from final harvest or clear-cut areas are only approximate, in that the presence of significant partial harvesting in the study region means that to obtain rotation age estimates one would need to adjust computations for amount of area partially harvested.

Natural vs Managed Disturbance Regimes

Comparing the management disturbance regime with historical, natural disturbance regimes can help us to understand the impact of management policies on ecosystems. Before the region was settled by Europeans, wildfire was the primary stand replacement disturbance (Agee 1993). Natural fire return intervals have been documented from only a few sites (Morrison and Swanson 1990; Impara 1997; Long and others 1998), but it is clear that they were quite variable. In the KMP, fire return intervals were around 30 years for low to moderately severe wildfires; in wet forests of the CRP, return intervals for high-severity fires may have been as long as 400 years. In much of the CRP and WCP, the fire return intervals probably ranged between 150 and 300 years (Morrison and Swanson 1990; Impara 1997; Long and others 1998). The fire return intervals reported in this study cannot be compared directly to historic numbers for at least three reasons. First, we report only fires of high severity. Second, the period of time studied here is short relative to historic return intervals. Finally, fire suppression activities were strong over the period of this study.

We know less about fire sizes and shapes. Fire size distributions were probably negatively skewed, with many small fires and a few large ones (Wimberly and others 2000). Large fires probably affected more of the total landscape than small fires. Wimberly and others (2000) used a mean fire size of 70,000 ha in modeling fires in the CRP, where fires are thought to be relatively large and severe (Impara 1997). In drier areas, many fires burned in a patchy manner, leaving unburned areas within them. In one landscape of the CRP, Morrison and Swanson (1990) estimated that burned patches within fires were typically less than 10 ha.

The aggregate clear-cut return interval observed for the entire area during the study period ranged between 85 and 225 years; this falls at the lower end of the range of the natural fire return interval. Not surprisingly, industrial forest management cutting return intervals (58 years) were one-half to one-fourth of what might be expected under a wildfire regime. Rates of cutting on private nonindustrial and public lands were much more similar to the disturbance rate of the wildfire regime. Cutting unit sizes are similar to patch sizes that might be expected in a patchy fire regime, based on the work of Morrison and Swanson (1990). Aggregate sizes are much smaller than the fire sizes that would be expected for single events.

Despite the similarity in rates of clear-cutting and historical stand replacement fires, the two disturbance regimes differ in many ways. First, wildfires can leave large patches of old forests intact, which means that a significant portion of stands older than the rotation age would persist in a landscape (Van Wagner 1978). In contrast, in a fully managed landscape, clear-cutting removes the oldest stands, leaving no stands older than the rotation age.

Second, fires occur throughout a landscape, albeit with different probabilities. In a managed landscape, there are typically some areas—such as unproductive lands, recreational areas, and wilderness areas—that are taken out of production and never experience planned disturbances, thus concentrating the disturbances in some parts of the landscape. This is especially the case on federal lands in the region, where wilderness areas are concentrated at higher elevations in less productive timber types. The relatively low rates of cutting we observed on federal land (202-year return interval) resulted from a total absence of cutting in wilderness and other reserve areas and a relatively high rate of cutting (probably about 80 years) on forests designated for timber production.

Third, there is a major difference in severity between the managed and natural disturbance regimes. Natural disturbances tend to leave live and dead legacies that are carried into the next stand. Clear-cut logging typically leaves little or no live and dead woody structures following disturbance. Of course, this difference in disturbance regimes is not detectable with the remote sensing that was used in our study. A discussion of the ecological consequences of these three differences is beyond the scope of this study, but there are clear implications for plant and wildlife habitat, carbon storage, and site productivity (Perry 1998).

Finally, although clear-cut unit and aggregate sizes are smaller than might be expected for fire events, the cumulative area of cutting can create large disturbance patches over a several-year period. Despite limits on clear-cut sizes, cutting may be concentrated in a landscape, creating a disturbance mosaic of hundreds to thousands of hectares.

Management Implications

Stand replacement disturbances occur both naturally (for example, fire, insects, windthrow) and by management prescription. Although both types of disturbance are important, they are quite different in their effects, especially in terms of return interval, size and shape, severity, and location on the landscape. Because harvest is by far the most extensive disturbance in the Pacific Northwest, there are a number of important policies in place to control it. As observed over the latter part of our study period, levels of timber harvest areas and volumes can change greatly in a short period of time, especially in response to socioeconomic or institutional changes. It could be useful to augment the existing sources of time-series data on harvest area, such as the remote sensing used in this study, with ground-based annual surveys. Developing a long-term database with ground-based surveys would help to identify harvest disturbances by forest cover types. In addition, an estimation of partial harvests could be made, which is more difficult to do with remotely sensed data. A combined approach using remote sensing and ground-based surveys is particularly important for effective monitoring of compliance with forest policy.

It would be easier to monitor human-related activities that affect forest ecosystems (for example, timber harvests) if remote-sensing data were supplemented with surveys of forest owners. In addition to examining the socioeconomic factors that influence owners' decisions on when to harvest, it would also be useful to learn why harvest unit sizes are so variable across owners. Since some of the private forests are fragmented into smaller pieces, monitoring should also include the analysis of forest fragmentation, which may ultimately lead to reduced economic viability and adverse ecological impacts.

Conclusions

- *In dense-canopied forests, stand replacement disturbance can be accurately monitored with Landsat data.* Using simple, cost-effective means, we mapped the occurrence of clear-cut harvesting and fire over 4.6 million forested hectares in western Oregon at roughly 5-year intervals, with nearly 90% accuracy.
- *Rates of harvest were variable by ownership.* The overall harvest trend was one of increasing rates between the early 1970s and the mid-1980s, followed by a general decline in harvest rates toward the mid-1990s. Private industrial landowners had rates of harvest that were about 2.5 times the rates of public landowners throughout the study period, reaching as high as 2.4% per year of its total land base at peak harvest rates. Responding to increased market prices during the study period, private nonindustrial landowners harvested at the lowest observed rates in the 1970s and then increased their harvest rates to those nearly as high as the rates of private industrial owners at the end of the study period.
- *Rates of harvest were variable by geographic province.* The Coast Range Province, which is dominated by private industrial landowners, experienced the highest concentrations of harvest, followed by the Western Cascades Province and the Klamath Mountain Province; this finding was commensurate with the declining proportion of private industrial ownership in those provinces.
- *Mean and variability of clear-cut unit size was considerably higher for private industrial landowners than for all other owner categories throughout the study period.* In addition, this ownership category

tended toward higher degrees of spatial aggregation of individual units over time than did all other categories of ownership.

- *Burn unit size and distribution were highly variable by geographic province.* The moist Coast Range Province had the largest and least frequent burns, whereas the Klamath Mountain Province had the smallest and most frequent burns.
- *The degree to which forest management can be effectively monitored with remote sensing remains an open question.* Changing forest policy and law are affecting forest management, and these changes are expressed spatially on the forest landscape. Although Landsat data are extremely valuable for assessing stand replacement disturbance in western Oregon, whether forest thinning and riparian zone management can be accurately detected with these data has yet to be determined. Most likely, some combination of Landsat data with inventory data and new types of remote-sensing data (such as lidar, hyperspatial, and hyperspectral) will be needed.

ACKNOWLEDGMENTS

This research was funded and/or supported by the Terrestrial Ecology Program and the Land-Cover Land-Use Change Program at NASA, the CLAMS study at the PNW Research Station and Oregon State University, the National Science Foundation-sponsored H. J. Andrews Forest LTER Program, and the EPA's National Health and Environmental Effects Research Laboratory, in Corvallis, Oregon. We dedicate this paper to the memory of John Gray in recognition of his valuable efforts towards development of the accuracy assessment methods used in this research. We also thank Julia Jones and Liane Guild, who helped us design the accuracy assessment strategy.

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Appendix. Landsat Imagery Used to Map Stand Replacement Disturbance

Satellite	Sensor	Year	Date	Path	Row
1	MSS	1972	2 September	49	28
1	MSS	1972	2 September	49	29
1	MSS	1972	29 July	50	28
1	MSS	1972	29 July	50	29
1	MSS	1973	18 June	50	31
1	MSS	1973	24 July	50	30
1	MSS	1973	28 August	49	30
1	MSS	1973	28 August	49	31
2	MSS	1976	16 July	49	29
2	MSS	1976	9 September	50	31
2	MSS	1977	16 August	49	28
2	MSS	1977	29 July	49	30
2	MSS	1977	29 July	49	31
2	MSS	1977	30 July	50	28
2	MSS	1977	30 July	50	29
2	MSS	1977	30 July	50	30
3	MSS	1982	12 October	51	28
3	MSS	1982	18 August	50	28
4	MSS	1983	27 April	47	29
5	MSS	1984	13 August	45	30
5	MSS	1984	13 August	45	31
5	MSS	1984	19 July	46	29
5	MSS	1984	19 July	46	30
5	MSS	1984	29 August	45	28
5	MSS	1984	29 August	45	29
5	MSS	1984	3 July	46	31
5	TM	1988	19 June	47	28
5	TM	1988	21 July	47	29
5	TM	1988	30 July	46	30
5	TM	1988	31 August	46	28
5	TM	1988	31 August	46	29
5	TM	1988	8 August	45	29
5	TM	1988	8 August	45	30
5	TM	1988	8 August	45	31
5	TM	1988	9 April	46	31
5	TM	1991	1 August	45	30
5	TM	1991	1 August	45	31
5	TM	1991	2 September	45	29
5	TM	1991	30 July	47	28
5	TM	1991	5 June	46	31
5	TM	1991	9 September	46	28
5	TM	1991	9 September	46	30
5	TM	1992	10 August	46	29
5	TM	1995	11 September	47	28
5	TM	1995	13 September	45	29
5	TM	1995	13 September	45	30
5	TM	1995	13 September	45	31
5	TM	1995	19 August	46	28
5	TM	1995	19 August	46	29
5	TM	1995	3 August	46	31
5	TM	1995	5 August	46	30