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An Efficient and Accurate Method for Mapping Forest Clearcuts in the Pacific Northwest Using Landsat Imagery

Warren B. Cohen, Maria Fiorella, John Gray, Eileen Helmer, and Karen Anderson

Abstract

Two variations of image differencing were compared. The first was based on unsupervised classification, repeated five times, using five sequential date-pairs of difference images between 1972 and 1993. Referred to as merged image differencing, this method required merging the results from five separate time intervals into a single map of forest harvest activity. The other method involved a single unsupervised classification of the full sequential difference image data set, and was referred to as simultaneous image differencing. A thorough harvest map error assessment using an independent reference database was compared to two methods of assessment based on visual interpretation of the Landsat data used to develop the difference images. Results indicate that harvest activity was mapped using merged image differencing with greater than 90 percent accuracy, and that visual methods of error assessment using the Landsat images gave nearly identical results with those of the independent reference data. Simultaneous image differencing resulted in a map that was consistent with merged image differencing, and was considerably more cost-effective to implement.

Introduction

Harvest of mature and old-growth forest and subsequent conversion to young forest in the Pacific Northwest region of the United States has been a contentious issue for well over a decade. The challenge has been to balance economic needs with a variety of ecological considerations, including sustainability of viable habitats for indigenous plants and animals, needs for clean, abundant water, and fluxes of greenhouse gases. This debate has stimulated several scientific studies by federal and other agencies and special interest groups to provide information needed by policy and law makers (USDA, 1993; USDA & USDI, 1994). Of fundamental importance to these studies is map-based vegetation data, including current forest cover and recent forest harvest activity.

There have been several independent efforts to map forest cover in the region (e.g., Morrison *et al.*, 1991; Congalton *et al.*, 1993; Cohen *et al.*, 1995), with several efforts ongoing to produce consistent, full spatial coverage vegetation maps from Landsat TM imagery for much of the region's forest land. Studies using Landsat imagery to map harvest activity include those of Thomas *et al.* (1993) for the Olympic Peninsula in the State of Washington, and Green *et al.* (1994) for a 52,000-ha area containing the Portland metropolitan region. For the latter study, two dates of TM imagery were used in conjunction with an image differencing algorithm. Although there was no substantive effort to independently assess mapping errors, a central conclusion from this study was that forest harvest activity could be mapped in a straightforward manner using an image differencing algorithm. The primary reason for this was that clearcut harvest areas exhibited significantly greater reflectance change than did any other type of vegetation change identified. The study by Thomas *et al.* (1993) used three dates of Landsat imagery (MSS and presumably TM) to map forest harvest, but the methodological details do not indicate how these data were analyzed, or whether there was any assessment of mapping errors.

Studies from other regions also indicate that clearcut forest harvest activity can be readily detected with Landsat data. Skole and Tucker (1993), seeking a straightforward and accurate method, visually located and digitized polygons around harvested units from hardcopy output of individual dates of TM imagery for the Amazon. Sader and Winne (1992) simultaneously projected three dates of NDVI images (derived from MSS and TM data) from the State of Maine through a video monitor's red, green, and blue color guns. Using a modified parallelepiped classification algorithm, and color additive theory, they interpreted and labeled a subset of color classes as harvest units. In Guatemala, Sader (1995) used a thresholding procedure on a two-date TM difference image to isolate three biomass change categories: stable, increase, and decrease. For all of these studies, error assessments were minimal. This was either because of difficult logistics (i.e., the sites were remote and aerial photography limited) or interpretations during the analytical phase were considered to be virtually unambiguous (i.e., harvest units were easily detected).

As part of a carbon flux modeling and mapping project (Cohen *et al.*, 1996), we are developing maps of forest harvest activity between 1972 and the near-present using Landsat data for all land between the Pacific Ocean and the crest of the Cascades Range in the states of Oregon and Washington. Because these maps will be made available to the general public, and are likely to be used for addressing a variety of contentious resource management issues outside of our own project, it is crucial that the maps developed be accurate, and that a credible means of assessing errors be developed. This is no simple task, given that there are over 14

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million ha of forest land in the project study area. As such, methods for mapping and error assessment must be relatively easy to apply and efficient to implement.

Objectives and Study Area

The study reported here is based on a 1.2-million-ha area in the central Oregon Cascade Range (Figure 1). This area has been the focus of our efforts to develop and test vegetation and carbon flux mapping methods using Landsat data for all of western Oregon and Washington (Cohen *et al.*, 1995; Cohen *et al.*, 1996). The area is representative of the full region of interest in several ways, including proportion of total land area that is forest, trends in harvest volume since 1972, and volume harvested per ha of forest land (Cohen *et al.*, 1996).

Forest lands of the Pacific Northwest region are owned and managed by a variety of public agencies and private industrial and non-industrial interests. The 1.2-million-ha area of this study is representative of that ownership mix (Figure 1). This area consists of much of the Willamette National Forest (FS), numerous tracts of other publicly owned forest land (BLM), large tracts of privately owned forest land, protected areas, and agricultural land. Many of the major forest types of the central and northern Cascade Range are represented, including the western hemlock/Douglas-fir, Pacific silver fir, and mountain hemlock forest zones (Franklin and Dyrness, 1988). Dense stands of western hemlock/Douglas-fir forests dominate the lower elevation range from the Willamette Valley fringe, at approximately 315 m to between 1100 m and 1250 m, with the other forest types dominating at higher elevations. Agricultural lands predominate below 315 m elevation.

The objective for this study were

- Develop a method to map clearcut forest harvest activity that is efficient as well as accurate. The specific change detection method involved was image differencing (Coppin and Bauer, 1996), but the algorithm was used in two distinct ways. The first was an analysis of five separate date-pairs, the results of which were merged into a final harvest map. This method was termed *merged image differencing.* An alternative approach, termed *simultaneous image differencing,* was to analyze the full temporal data set simultaneously.
- Characterize errors in a clearcut harvest map derived from Landsat data. This included comparisons of the harvest map with an independent vector database containing forest stand historical information, and by two methods involving visual inspection of all single date images that were used in the image differencing algorithm. Because using a vector database (if one even exists) can be logistically difficult and potentially costly, the intent was to determine if visual inspection methods using the Landsat data give results that are consistent with use of this independent database.

TABLE 1. IMAGES USED FOR FOREST HARVEST MAPPING.

Date	Sensor	Scene ID#
02 Sep 1972	MSS	8104118265500
16 Jul 1976	MSS	8254118082500
19 Jul 1984	MSS	5014018254
31 Aug 1988	TM	5164418271
07 Jul 1991	TM	5268418193
29 Aug 1993	TM	94082005-01

Methods

A of total of six Landsat images were used in this study to detect forest harvest activity between 1972 and 1993 (Table 1). Initially, merged image differencing was the only method to be tested and, for the 1.2-million-ha area under investigation, all six images were used. Upon completion of the initial analysis, a more efficient procedure was sought, and the

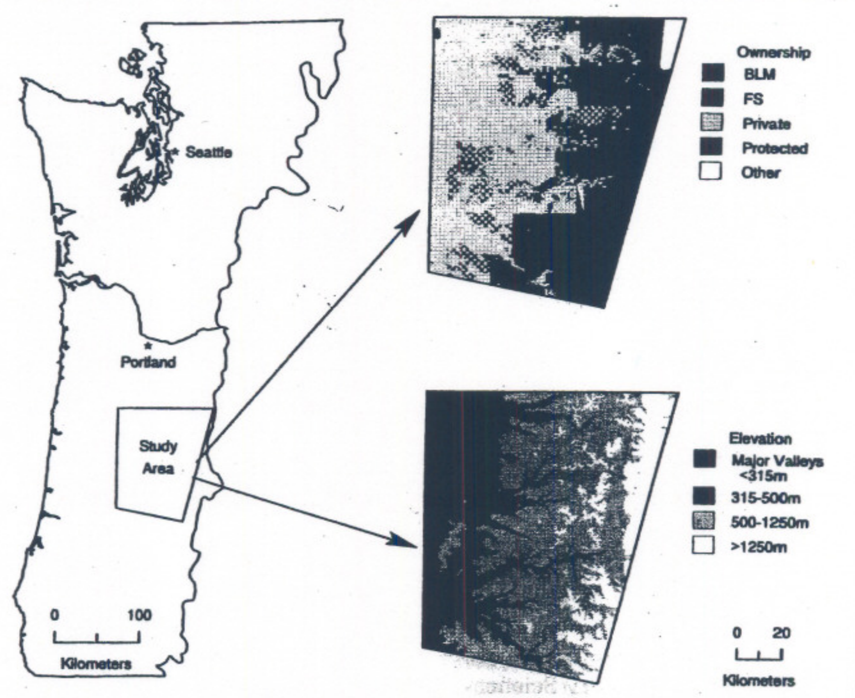

Figure 1. Study area for the work reported here, shown within the context of the full 14-million-hectare area for which methods will be later applied. Also shown are ownership and elevation data for the study area (FS = USDA Forest Service; BLM = USDI Bureau of Land Management).

simultaneous image differencing approach was devised. At this same time, it was apparent that funds were not available to purchase and process 1993 images for the full 14-million-ha forest area associated with the larger carbon flux project that this study was a part of. Thus, for the simultaneous image differencing approach, the temporal extent of the analysis was reduced, and the 1993 image was not used.

The 1988 TM image was made available for this study in precision geocoded (25-m cell size) format, and all other MSS and TM images were georeferenced to it using 36 ground control points. All georeferenced images were resampled to 25 m using a maximum second-order polynomial, with less than 1 pixel RMSE. The resampling of MSS images to 25 m was a matter of convenience, but this did not increase the effective resolution of the data. The 1.2-million-ha study area was subset from the full, multi-date image data set. Water bodies and areas below 315 m elevation (the level below which agricultural activity predominates), as determined from a digital elevation model (Figure 1), were masked from the images. Although radiometric normalization of multi-temporal image data sets, to account for differences in atmospheric and illumination conditions, is recognized as important for digital change detection, no such corrections were made in this study. The effort/cost required for radiometric normalization was considered greater than the expected benefit, given that the "signal" from the type of change sought, forest to non-forest, was expected to be significantly greater than the "noise" that was not compensated for. Although there likely was some residual change detection error associated with not having normalized the images, visual inspection of the images confirmed that the signal from harvest activity was far greater than any noise due to variable atmospheric and illumination angle conditions among dates.

All MSS data were transformed into the MSS Tasseled Cap brightness and greenness vegetation indices (Kauth and Thomas, 1976), and all TM data into TM Tasseled Cap brightness, greenness, and wetness indices (Crist *et al.*, 1986). This choice of spectral variables was based on the fact that coniferous forest stands of the Pacific Northwest have high leaf area index, causing them to have low brightness and high greenness and wetness relative to forest clearcuts (Cohen *et al.*, 1995). Thus, the main impact of forest harvest on ground scene reflectance would be an increase in harvest patch brightness and a decrease in greenness and wetness. Brightness and greenness (and, for TM, wetness) difference images were created for each time interval by subtracting the older image from the more recent image (i.e., 1976–1972, 1984–1976, 1988–1984, 1991–1988, and 1993–1991).

Merged Image Differencing

Map Development

Merged image differencing involved evaluation of individual date-pair Tasseled Cap difference images, the results of which were merged into a single map representing harvest activity between 1972 and 1993. Because the first three date intervals involved MSS data, only brightness and greenness difference images were analyzed. For the latter two intervals, both involving only TM data, brightness, greenness, and wetness difference images were analyzed. Difference images for each interval were subjected to a statistical clustering algorithm (i.e., unsupervised classification). Interpretation and labeling of clusters was accomplished solely with the aid of visual interpretation of original, interval end-point Tasseled Cap images. Clusters were initially labeled as "forest-harvested," "forest-not-harvested," or "confused." Confused clusters were iteratively reclustered, using the cluster busting technique of Jensen *et al.* (1987), until confusion was minimized. After each date-pair difference image was segmented into forest-harvested and forest-not-harvested, they were combined (i.e., merged) using a GIS overlay operation. The forest-not-harvested class consisted of forest areas that were observed to undergo no severe disturbance, or that had exhibited succession from one forest class to another (e.g., an area of early-successional brush condition that became a conifer forest).

The resulting harvest map had two obvious sources of error: error due to spatial misregistration of the multi-temporal data set, and error due to a transitory snow zone in the high, nonforested mountains. To minimize the effects of misregistration, the map was smoothed using a 7 by 7 majority filter. Although a smaller window size may have been sufficient for this, a 49-pixel window also tended to eliminate classified harvest units that were below an expected minimum size of about two hectares. Errors in the snow zone were minimized by using aerial photos to assist in precisely locating the non-forest snow zone and then relabeling all pixels within that zone to non-forest. There were no forested areas containing snow in any of the images. All agricultural lands and water bodies originally masked from the images were also labeled as non-forest. All images used were free of clouds.

Map Error Assessments

Three different methods were used to quantify errors in the harvest map. The first involved an independent vector database, whereas the second and third involved visual interpretation of input Landsat images. One visual interpretation method was patch-based, whereas the other was pixel-based. The non-forest class was not sampled during the first two procedures.

Independent Vector Database

Historic forest stand inventory and management data were sought for comparison with the harvest map. The Willamette National Forest of the USDA Forest Service does not maintain a digital database containing this historic information, and obtaining records for individual clearcut units from folders in various file cabinets at district offices was an undesirable option. Forest data of the USDI Bureau of Land Management (BLM) are maintained at district offices in a common GIS format. These data from the Salem and Eugene Districts Offices were made available for this study, which enabled assessment of map errors throughout the full north-south extent of the study area (Figure 1). Forest land in the eastern portion of the study area are primarily Forest Service lands and, thus, were not represented in this database. The minimum forest stand size in the BLM forest database is 2 ha. Contained in the digital files for each stand are a georeferenced polygon and a number of fields that could be used to determine if, and when, the stand was clearcut. These are "denudation date" and "yarding date," associated with harvest, and "birth date," associated with date of planting following harvest.

Initially, assuming the database to be 100 percent correct, only the denudation date was used for selection. Therefore, from the district databases, stands with denudation date values between 2 September 1972 and 29 August 1993 (the time period of this study, as per Table 1) were selected. A preliminary assessment indicated that some 40 percent of the mapped harvest patches were not represented by stand polygons selected from the BLM database. A possible explanation was that some BLM stands had been harvested, but their polygons had not been assigned a denudation date. Consequently, the database was searched again, this time for a yarding date and birth date. The number of selected stands increased by over one-half.

A number of digital methods for comparing the map with the vector database were attempted. The method found to be most effective was to use a GIS operation to locate the centroids of BLM harvest polygons, overlay these on the harvest map, and count the number of harvest patches containing a centroid, the number of patches not containing a centroid, and the number of centroids not falling within a patch. For each patch the date interval was noted, and for each centroid the date was noted. This procedure allowed for slight spatial misregistration errors between the data sets, eliminated the occurrence of polygons in the BLM database intersecting more than one patch in the harvest map, and permitted an error assessment by harvest map time interval.

Visual Patch-Level Interpretation of Landsat Images
Six harvest-map subareas of 2500 ha (200 by 200 pixels) of mixed ownership were chosen to represent various terrain elevations and cutting patterns. For each subarea, the six original Tasseled Cap brightness and greenness (and wetness where applicable) images used to create the difference images were displayed. Without reference to the harvest map, all patches visually interpreted as harvest during a given time interval and greater than 2 ha were digitized. For geographic consistency, all digitizing was done over the original 1993 image. A total of 196 polygons were digitized, ranging from 12 to 55 polygons per subarea. Total area of digitized polygons was compared to harvest map area on both subarea and time interval bases.

Visual Pixel-Level Interpretation of Landsat Images
A total of 250 individual pixels were randomly sampled without replacement from the harvest map, equally divided between the forest-harvested and the forest-not-harvested classes. Each pixel from the forest-harvested sample had a mapped harvest time interval associated with it, which permitted an error evaluation by time interval. The six original brightness and greenness (and wetness where applicable) images that were used to create the difference images were compared for evaluation of the 250 sample pixels. This comparison involved a simple, visual interpretation for each sample pixel of the type of change, if any, that occurred. The individual pixels were examined in the context of neighboring pixels, but the map label for sampled pixels was unknown during this procedure. When visual interpretation indicated harvest, the interval of harvest was noted.

Approximately 5 percent of the 250 sample pixels fell along a forest/clearcut boundary. Although the harvest map was smoothed, the original and difference images used to develop it were not. Thus, when these images were inspected, slight misregistration among the dates of imagery made determination of forest-harvested versus forest-not-harvested difficult for these boundary pixel samples, and these pixels were excluded from the error analysis.

Simultaneous Image Differencing

Map Development

The merged image differencing approach involved the development of single time-interval maps that were subsequently merged into a single harvest map. As such, iterative statistical clustering and labeling had to be repeated for each time interval. To reduce the number of steps required to map forest harvest activity, an alternative, simultaneous image differencing method was used. With this approach, iterative clustering and labeling were done only once for the whole temporal set of difference images. Although simultaneous image differencing represented a potentially significant time savings, the potential for error may have been greater.

For this study, a second harvest map was created for the same ground area using the simultaneously image differencing approach with the four date-interval difference images between 1972 and 1991. As wetness does not exist for the MSS data, only brightness and greenness difference images were included for all intervals. The same statistical clustering procedure used for merged image differencing was used here. Also, as cluster labeling was based on visual interpretation of original Tasseled Cap images, harvest activity was labeled by time interval.

Map Agreement

Rather than repeat the error assessment procedures used for the original harvest map, the level of agreement between the two harvest maps was evaluated. If the two maps exhibited a high level of agreement, then it was safe to assume that, between the two maps, errors were similarly distributed among mapped classes. Agreement was characterized in two ways: (1) based on overall area harvested and (2) based on a spatially explicit, pixel-by-pixel comparison using a map overlay function. For this comparison, the forest-harvested class from the 1991-1993 time interval of the merged image differencing map was relabeld to forest-not-harvested.

Results and Discussion

Merged Image Differencing Harvest Map

Of the total 1.2-million-ha study area, 897,939 ha were mapped as forest land, 14.7 percent of which was harvested between 1972 and 1993 (Plate 1). This translates to a cutting rate of 0.7 percent per year. Patterns of cutting are strongly associated with land ownership category (Figure 1). On private forest land, individual clearcuts tend to be larger than on public lands, and are spatially aggregated over time. Clearcuts on public lands generally occur as individual patches, resulting in a fragmented appearance. An in-depth analysis of harvest activity in the region is the subject of a follow-on paper.

Error Assessments

Independent Vector Database
Of 982 total observations associated with the BLM data base, 97 percent involved harvest patches containing a centroid. Four percent of these involved BLM centroid dates occurring one time interval earlier than indicated on the harvest map (Table 2). There were no occurrences of harvest map time interval preceding BLM polygon centroid date. Thus, on a time-interval basis, the harvest map had errors on the order of 7 percent.

Visual Patch-Level Interpretation of Landsat Images
This error assessment was done on an area basis by comparing polygons digitized around visually interpreted harvest patches in the original Tasseled Cap imagery with harvest patches in the harvest map. Polygon and patch areas were summed by subarea and by date interval. Results on a subarea basis show that proportional differences between digitized polygons and harvest map patches were consistently small (−6 percent to +2 percent) among subareas when all intervals were summed (Table 3). The same was generally true among individual intervals summed across subareas, except for a relatively large difference of +13 percent for the 1972-1976 interval (Table 4). This commission error could be associated with the relative poor quality of early MSS data. Another possibility is that areas harvested prior to 1972 were not detected as harvested until after 1972. Harvested units are often burned prior to planting, which would cause them to have low brightness similar to older forests. Normally, within a two-to-three year period, these units become significantly brighter than surrounding forest areas, as the burned material becomes covered by regrowing early-successional vegetation. When visually interpreting the original Tasseled

Cap images, the distinction between burned clearcuts and older forests is clear, but in a difference image, this is not the case. Overall, across subareas and time intervals, total area of harvest on the map differed by less than 1 percent from the hand-digitized area.

Visual Pixel-Level Interpretation of Landsat Images

Of the 250 pixels sampled, three from the forest-not-harvested sample and ten of the forest-harvested sample fell along the forest/clearcut boundary and were not included in the error assessment. Of the total number of pixels remaining that were classified as forest-harvested, 90 percent (104/115) were harvested during the time interval mapped (Table 5). Seven percent of the pixels classified as forest-harvested during a given interval (8/115) were actually harvested one time interval earlier. This was due to clearcuts that had been recently burned, as described in the last section. Two percent (3/115) of the pixels mapped as harvested were actually not harvested, but had apparently experienced vegetation phenological changes that caused them to be mapped as clearcut.

Of all the sampled pixels mapped as non-harvest, only one percent were actually harvested. These were in very small clearcuts that had been originally mapped as harvest, but were eliminated during the smoothing process.

Table 2. Results from Comparison of the BLM Vector Database with the Merged Image Differencing Harvest Map.

Outcome	Number of Observations	Percent of Total
Agreement	915	93.2
Reference earlier than map	38	3.8
Reference later than map	0	0.0
No reference polygon	29	3.0
No mapped patch	0	0.0
Totals	982	100.0

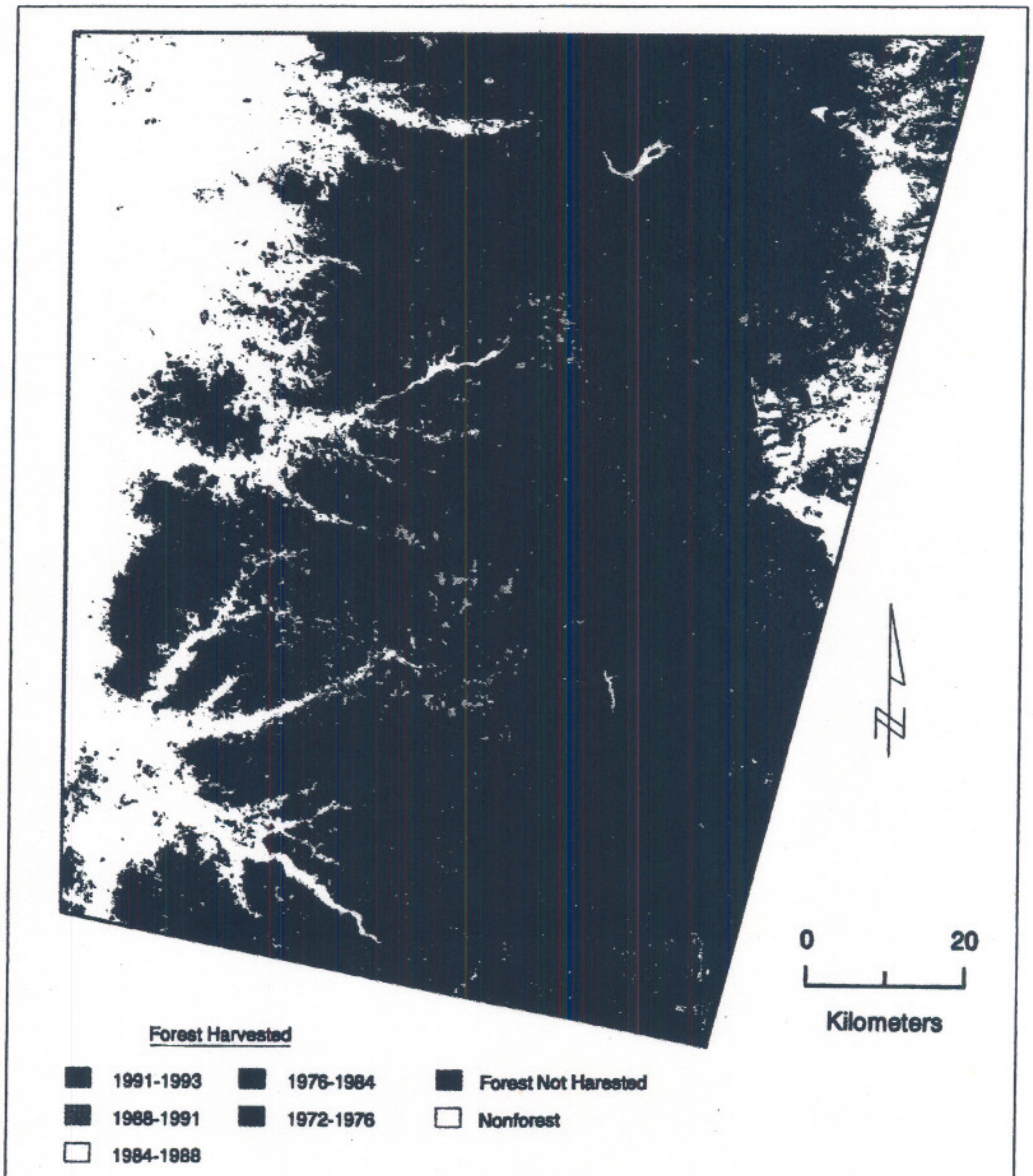

Plate 1. The merged image differencing harvest map showing areas harvested by time interval.

TABLE 3. COMPARISON, BY SUB-AREA, OF TOTAL AREA DIGITIZED ON THE MERGED IMAGE DIFFERENCING HARVEST MAP TO AREA DIGITIZED ON TM IMAGES.

Sub-area	No. of Polygons Digitized	Digitized Area (ha)	Harvest Map Area (ha)	Percent Difference
1	12	268	262	−2.2
2	32	644	633	−1.7
3	45	375	354	−5.6
4	15	262	249	−5.0
5	55	487	471	−3.3
6	37	1751	1791	+2.3
Totals	196	3787	3760	−0.7

Combining the results for forest-harvested and forest-no-tharvest pixels, errors in the map are less than 6 percent (104 forest-harvested pixels plus 112 forest-not-harvested pixels divided by 237, the number of pixels sampled not falling on a clearcut/forest boundary). Ignoring time interval, errors were less than 3 percent (this counts the burned clearcut to bright clearcut as correct).

Simultaneous Image Differencing Harvest Map

Agreement between the simultaneous image differencing harvest map and the merged image differencing harvest map was evaluated in two ways. On a total area, non-spatial basis, by time period, the difference in detected harvest activity varied from −0.4 percent to +1.6 percent (Table 6). Across the full time interval from 1972 to 1991, the harvest activity represented in the simultaneous image differencing harvest map was only 0.8 percent more than that represented in the merged image differencing harvest map.

On a spatial basis, agreement between the two maps is illustrated in Figure 2. Overall, across time periods, there was 92.5 percent agreement between the two maps that 12.1 percent and 80.4 percent of the forest area was harvested and nonharvested, respectively. A decrease of only 1.7 percent agreement was attributable to temporal error; i.e., overall agreement in both time and space was 90.8 percent.

Summary and Conclusions

This study sought to map clearcut harvest activity in the Pacific Northwest region of the United States in an accurate and efficient manner using historic Landsat imagery. Two related image differencing methods were tested. One method was based on unsupervised classification, repeated five times, using five sequential date-pairs of difference images (referred to as merged image differencing). The results were then merged into a single map of forest harvest activity from 1972-1993. The other method involved a single unsupervised classification of the full sequential difference image data set, and is referred to as simultaneous image differencing.

Other studies have indicated that clearcut logging can be readily detected using Landsat imagery, mainly because this type of cover change in forest land is expressed as a large spectral contrast in a temporal image data set. However, none of these studies substantiated this claim with a rigorous error assessment. This study conducted a thorough harvest map error assessment using an independent reference database, and compared these results to two methods of assessment based on visual interpretation of the digital image data used to develop the difference images. One visual method was based on harvest patches, whereas the other was pixel-based.

Comparison of the merged image difference harvest map with the independent reference database indicates that, across the full time period from 1972 to 1993, an overall accuracy of 97 percent was achieved. However, 4 percent of this 97 percent was mapped as having been harvested one time interval earlier than the reference data had indicated. The visual patch-based interpretation of harvest area indicated that the harvest map contained 1 percent less harvest area than was actually harvested between 1972 and 1993. On a time-interval basis, however, the harvest map and the results of visual harvest patch interpretation differed between +13 percent and −5 percent. The pixel-based visual error assessment indicated that the harvest map was 94 percent accurate, on a time-interval basis. Three percent of this error was associated with burned clearcuts that caused classification of harvest to be delayed by one time interval. Thus, based on the pixel assessment across the full time period from 1972 to 1993, the harvest map was 97 percent accurate.

Taken together, each of the three error assessments on the merged image difference harvest map indicate that clearcut harvest activity was mapped using Landsat data with an accuracy in excess of 90 percent. Of the less than 10 percent error observed, several percentage points were associated with a time interval error. Of these, the greatest errors were associated with the early time periods for which MSS data were used. That all three assessment methods gave similar results, is a very important point. For situations where inde-

TABLE 4. COMPARISON, BY TIME INTERVAL, OF TOTAL AREA DIGITIZED ON THE MERGED IMAGE DIFFERENCING HARVEST MAP TO AREA DIGITIZED ON TM IMAGES.

Date Interval	No. of Polygons Digitized	Digitized Area (ha)	Harvest Map Area (ha)	Percent Difference
1972-1976	31	381	429	+12.6
1976-1984	62	1481	1472	−0.6
1984-1988	44	847	786	−7.2
1988-1991	40	862	866	+0.5
1991-1993	19	216	207	−4.2
Totals	196	3787	3760	−0.7

TABLE 5. VISUAL INTERPRETATION OF TYPE OF FOREST CHANGE FOR SAMPLED PIXELS CLASSIFIED AS FOREST-HARVESTED ON THE MERGED IMAGE DIFFERENCING HARVEST MAP. GIVEN ARE NUMBERS OF PIXELS, BY TIME PERIOD TO WHICH THE SAMPLES WERE MAPPED. FOREST TO CLEARCUT REPRESENTS CORRECT CLASSIFICATION WITHIN THE STATED TIME INTERVAL. BURNED CLEARCUT TO BRIGHT CLEARCUT REPRESENTS MISCLASSIFICATION WITH RESPECT TO TIME INTERVAL, IN THAT THESE SAMPLES ARE FROM AREAS THAT WERE FOREST CONVERTED TO CLEARCUT, BUT THAT WERE NOT DETECTED AS CLEARCUT UNTIL ONE TIME-INTERVAL LATER. THUS, IF TIME INTERVAL IS IGNORED, THIS TYPE OF ERROR DOES NOT REPRESENT MISCLASSIFICATION. PHENOLOGICAL CHANGE REPRESENTS AREAS THAT WERE NOT CLEARCUT, BUT THAT WERE MAPPED AS CLEARCUT BECAUSE OF OBSERVED SPECTRAL CHANGE.

Type of Change	1972-1976	1976-1984	1984-1988	1988-1991	1991-1993	1972-1993
Forest to clearcut	17	19	30	15	23	104
Burned clearcut to bright clearcut	4	2	1	0	1	8
Phenological change	0	0	1	1	1	3
Percent correct	81	90	94	94	92	90

TABLE 6. PERCENT OF FOREST LAND HARVESTED, BY TIME PERIOD, AS REPRESENTED BY EACH OF THE TWO MAPS. ALSO GIVEN ARE DIFFERENCES RELATIVE TO THE MERGED TEMPORAL HARVEST MAP.

Harvest Map	1972-1976	1976-1984	1984-1988	1988-1991	1972-1991
Merged image difference	3.23	5.58	3.43	3.21	15.45
Simultaneous image difference	3.08	5.22	5.05	2.90	16.25
Difference	−0.15	−0.36	1.62	−0.31	0.80

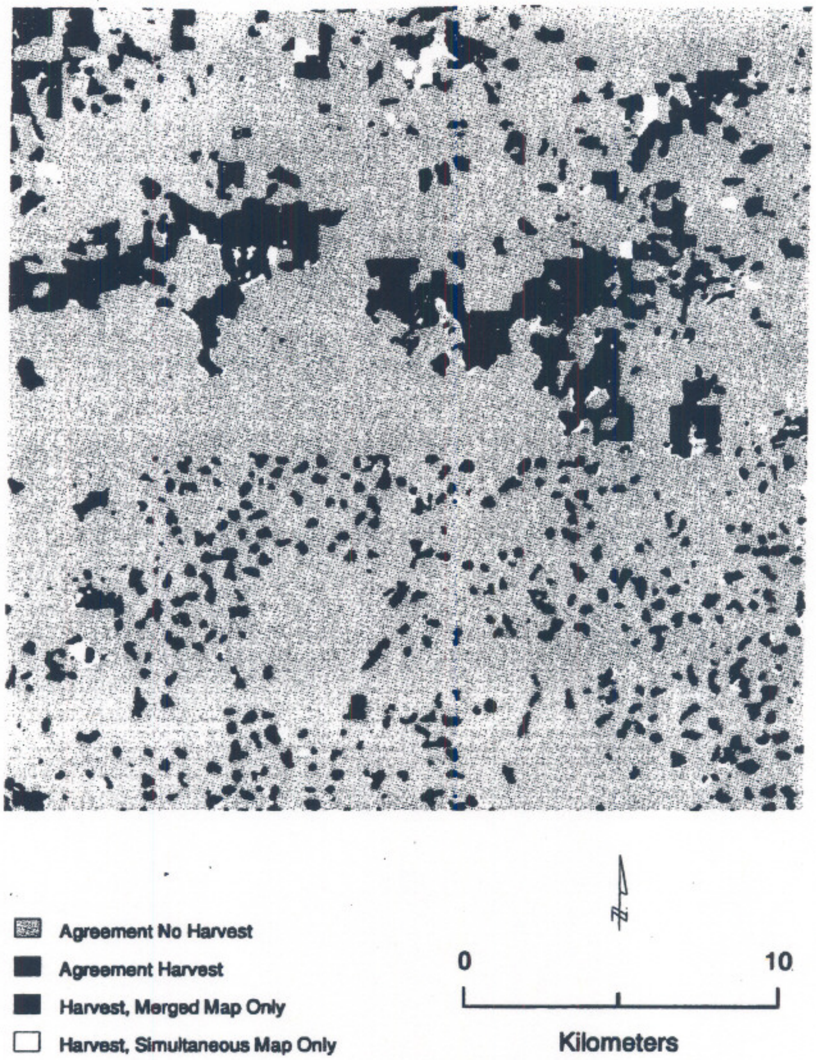

Figure 2. Agreement between the merged and simultaneous image differencing harvest maps for a subset of the study area.

pendent reference data are unavailable, a visual assessment comparing the Landsat data to the harvest map is a credible means of assessing map error. Moreover, even when such independent data are available, the cost of obtaining and processing them may render them an undesirable option relative to visual assessment techniques.

The harvest map developed by simultaneous unsupervised classification of the full temporal image difference data set had less than 1 percent more harvest area across all time intervals than did the map based on merging the results of five separate classifications. The maps differed in harvest area by less than 2 percent, for any given time interval. A pixel-by-pixel comparison of the two maps indicated an overall 93 percent agreement across time intervals. The same comparison, by time interval, reduced this agreement by 2 percent.

Because the simultaneous image differencing method involves a single unsupervised classification procedure, it was considerably more efficient than the merged image differencing method that involved one classification procedure for each time interval evaluated. Given that the map resulting from the simultaneous method was less than one percent different in terms of mapped harvest area, and that on a pixel-by-pixel basis, the maps were exactly the same on 93 percent of the map, the simultaneous image differencing method is very efficient and thus cost-effective.

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References

Cohen, W.B., T.A. Spies, and M. Fiorella, 1995. Estimating the age and structure of forests in a multi-ownership landscape of western Oregon, U.S.A., *International Journal of Remote Sensing*, 16: 721–746.

Cohen, W., M. Harmon, D. Wallin, and M. Fiorella, 1996. Two decades of carbon flux from forests of the Pacific Northwest, *BioScience*, 46:836–844.

Congalton, R.G., K. Green, and J. Teply, 1993. Mapping old growth forests on national forest and park lands in the Pacific Northwest from remotely sensed data, *Photogrammetric Engineering & Remote Sensing*, 59:529–535.

Coppin, P., and M. Bauer, 1996. Digital change detection in forested ecosystems with remote sensing imagery, *Remote Sensing Reviews*, 13:207–234.

Crist, E.P., R. Laurin, and R.C. Cicone, 1986. Vegetation and soils information contained in transformed Thematic Mapper data, *Proceedings, IGARSS '86 Symposium*, Zürich, Switzerland, 8-11 September 1986, ESA Publications Division, SP-254:1465–1470.

Franklin, J.F., and C.T. Dyrness, 1988. *Natural Vegetation of Oregon and Washington, Second Edition*, Oregon State University Press, Corvallis, Oregon.

Green, K., D. Kempka, and L. Lackey, 1994. Using remote sensing to detect and monitor land-cover and land-use change, *Photogrammetric Engineering & Remote Sensing*, 60:331–337.

Jensen, J.R., E.W. Ramsey, H.E. Mackey, E. J. Christensen, and R.R. Sharitz, 1987. Inland wetland change detection using aircraft MSS data, *Photogrammetric Engineering & Remote Sensing*, 53: 521–529.

Kauth, R.J., and G.S. Thomas, 1976. The tasseled cap — a graphic description of the spectral-temporal development of agricultural crops as seen by Landsat, *Proceedings on the Symposium on Machine Processing of Remotely Sensed Data*, 4b:4151, 6 June-2 July, 1976, LARS, Purdue Univ., West Lafayette, Indiana.

Morrison, P.H., D. Klopfer, D.A. Leversee, C.M. Socha, and D.L. Ferber, 1991. *Ancient Forests in the Pacific Northwest, Analysis and Maps of Twelve National Forests*, The Wilderness Society, Washington, D.C., 22 p.

Sader, S.A., 1995. Spatial characteristics of forest clearing and vegetation regrowth as detected by Landsat Thematic Mapper imagery, *Photogrammetric Engineering & Remote Sensing*, 61: 1145–1151.

Sader, S.A., and J.C. Winne, 1992. RGB-NDVI colour composites for visualizing forest change dynamics, *International Journal of Remote Sensing*, 13:3055–3067.

Skole, D., and C. Tucker, 1993. Tropical deforestation and habitat fragmentation in the Amazon: Satellite data from 1978 to 1988, *Science*, 260:1905–1910.

Thomas, M., N. Roller, J. Colwell, and C. Kottack, 1993. Integrating regional studies of deforestation into a global change context, *Proceedings, 25th International Symposium, Remote Sensing and Global Change*, Volume 1, Environmental Research Institute of Michigan, Graz, Austria, 4-8 April, pp. 559–570.

USDA [United States Department of Agriculture], 1993. *Forest Ecosystem Management: An Ecological, Economic, and Social Assessment*, Report of Forest Ecosystem Management Assessment Team, USDA Forest Service, Ogden, Utah.

USDA & USDI [United State Department of Agriculture & United States Department of Interior], 1994. *Record of Decision (for Amendments to Forest Service and Bureau of Land Management Planning Documents within the Range of the Northern Spotted Owl) and Standards and Guidelines (for the Management of Habitat for Late-Successioinal and Old-Growth Forest Related Species Within the Range of the Northern Spotted Owl)*, April 1994.

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