3 Remotely Sensed Data in the Mapping of Forest Harvest Patterns

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CONTENTS

INTRODUCTION

The economic value of the timber, paper, and fuel products extracted from forests has made forest harvesting one of the primary agents of forest disturbance globally. In addition to economic importance, forest harvests can have significant ecological consequences. Harvest levels have in some cases been observed to significantly affect wildlife habitat (Curtis and Taylor, 2004; Richards et al., 2002) and influence biogeochemical (Cohen et al., 1996; Hassett and Zak, 2005) and hydrological (Swank et al., 2001) cycles. This chapter summarizes a range of forest harvest practices by way of creating a framework for understanding data and method considerations specific to forest harvest detection. There are several thorough reviews of digital change detection methodology (Coppin et al., 2004; Gong and Xu, 2003; Singh, 1989). With those works as background, the focus here is on how the physical characteristics of various silvicultural operations influence data and method considerations in the change detection process. A case study involving detection of stand-replacing harvests in the Pacific Northwest of the United States of America is used to illustrate the process of selecting data and methods to address a particular set of analytical and mapping needs.

SILVICULTURAL OPTIONS

Silviculture is the science of manipulating ecological processes with a goal of shaping the structure of a forest stand to meet management goals. Harvesting, in addition to often yielding merchantable forest products, is a primary tool in this manipulation. The term *harvest* is used here to represent the cutting of any trees, even if that cutting does not produce salable products. In this section, harvests are broken into three different kinds of cuts: regeneration harvest, thinning, and salvage. This organization of harvest operations is based on silvicultural intent; regeneration harvest is intended to stimulate growth of a new cohort of trees, thinning is intended to stimulate growth of existing trees, and salvage is regeneration neutral, focusing mainly on extracting dead or dying trees that would otherwise become unusable. Salvage harvests have also on occasion been classified as a type of thinning when undertaken to remove suppressed trees proactively (e.g., Smith et al., 1997). However, only salvage that follows another disturbance is discussed in this chapter.

Although it is true that most remotely sensed data are fundamentally quantitative and not always suited to identifying silvicultural distinctions based on long-term intentions, there are nevertheless good reasons for becoming familiar with silvicultural theory. First, the management records often used as reference data in harvest mapping projects are likely to describe harvests in silvicultural terms (e.g., Franklin et al., 2000). Also, awareness of typical harvest strategies, some of which include a number of stand entries, can facilitate interpretation of the spectral data. This is particularly true if certain assumptions based on forest type and ownership can be used to predict likely harvest strategies in a given region. This section describes differences between regeneration, thinning, and salvage cuts and discusses the role of these harvest types within specific silvicultural systems.

REGENERATION HARVEST

Regeneration harvest (often called stand-replacing harvest) involves the removal of trees with the intention of stimulating the development of a new cohort of trees. In silvicultural systems using even-age stands, regeneration harvests can take the form of a clearcut, where all trees are removed, or a retention harvest, where some trees are allowed to survive for a variable length of time into the next rotation (Figure 3.1). Clearcuts are often chosen by industrial forest landowners because they are simple to administer and because they create exposed conditions that favor a large group of commercially important shade-intolerant species (Oliver, 1981). There are several reasons that a landowner may temporarily retain trees in what otherwise

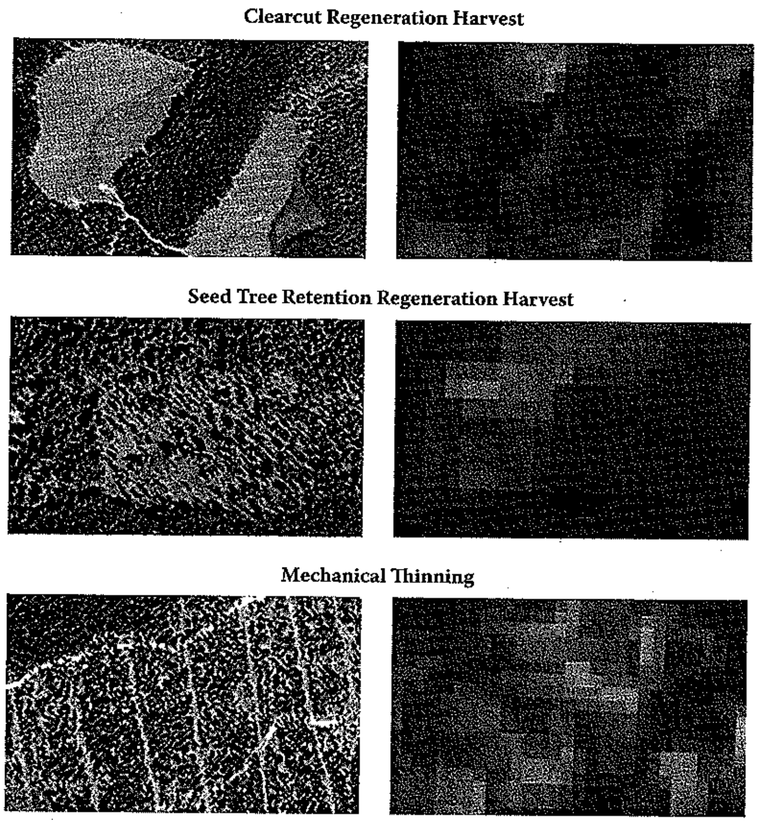

FIGURE 3.1 (See color insert following page 146.) Common harvest practices represented in color orthophotos and tasseled cap-transformed (Crist and Cicone, 1984) Landsat data. Both sets of images were acquired in 2002 and show closed-canopy coniferous forests in central Washington State.

would be a clearcut: as a seed source, to moderate microclimatic conditions for the new cohort in a "shelterwood" capacity, or simply to diversify the structure of the succeeding stand for wildlife or aesthetic purposes (British Columbia Ministry of Forests, 2003). Trees in these systems may be left in densities and spatial distributions that are as various as the reasons for leaving them. The confusing aspect of retention cuts from the point of view of the remote sensing analyst is that even if retained trees are left in detectable densities, their sometimes gradual removal can occur at a stage when the rest of the stand is growing vigorously.

Related to even-age regeneration harvests are conversion cuts. Cutting all or most of the trees in a stand for the purpose of changing to a nonforest land use is not technically a silvicultural treatment, so it has no place in established silvicultural systems. Nevertheless, forest conversion is common throughout the world, particularly in the tropics, where shifting agricultural systems are employed (Achard et al., 2002). Losses of forest are also common on the forest/urban interface (Kline et al., 2004). While initially indistinguishable from even-age regeneration harvests, conversion cuts become identifiable over time as they fail to show a spectral signature consistent with forest recovery.

Some regeneration harvests are designed to create a multiage stand structure. Often called *selective harvests*, these cuts take out at least enough canopy and understory trees to stimulate regeneration of a new cohort. The intensity of removal can vary depending on the growth properties of the new trees, the preharvest structure of the stand, and both long- and short-term economic concerns. The management of multiage forests is considerably more complex than even-age forest management, primarily because competition must be managed between cohorts as well as within cohorts. Commitment to this more complex management by industrial forest owners is not common (Maguire, 2005); in practice, true selection harvests typically occur in places where, perhaps for wildlife or aesthetic reasons, uneven stand structure is a goal in itself.

Thinning

The silvicultural distinction between partial regeneration harvest and thinning is that regeneration harvest is intended to stimulate the growth of a new cohort of trees, whereas thinning is not. Smith et al. (1997) outlined four distinct approaches to thinning that are summarized here: low thinning, crown thinning, selective thinning, and geometric thinning. Low thinning involves the removal of trees below a chosen size. Usually, this means removing trees from suppressed and intermediate crown classes to benefit trees in co-dominant and dominant positions. This system is traditionally most common when suppressed trees are merchantable, often as firewood (Smith et al., 1997). A considerable amount of attention has recently been given to this type of thinning as a means to reduce forest fuels in fire-prone landscapes in the American west (Brown et al., 2004; Fight, 2004), although other types of thinning have also been considered (Fiedler, 2004). Low thinning has likewise been considered as a way to remove the less-vigorous trees that are particularly vulnerable to insect attack (Oliver and Larson, 1996). Recent forest legislation makes thinning that reduces forest health risks, a management priority (Healthy Forests Restoration Act, 2003), so low thinning may occur on public lands with increasing frequency.

As opposed to low thinning, which eliminates trees with growth rates that have already been suppressed, crown thinning involves the harvest of trees in the upper canopy classes to favor more vigorous or better-formed competitors. This practice is much more common than low thinning on industrial forest land for at least two reasons. First, the products of crown thinning are more often merchantable than the by-products of low thinning. Second, since it is large, vigorous trees that are removed, more of the site's resources are released to remaining trees, resulting in larger gains in the annual increment of the "crop" trees (Smith et al., 1997). Thinning of dense young stands also falls into this category, although the trees cut in these cases typically have limited commercial value. Such density management thins are common not only in intensively managed plantations, but also in naturally regenerated stands (Doruska and Nolen, 1999; Wilson and Oliver, 2000). Smith et al. (1997) suggested that this type of thinning makes most sense on poor sites where the limitation of a critical resource prevents structural differentiation of the canopy into distinct strata.

The third type of thinning, selective thinning, may appear quite similar to crown thinning in that both involve the thinning only of trees in the upper strata. The difference between the two approaches lies in the selection of trees to be left. Crown thinning involves cutting co-dominants to favor dominant trees, whereas in selective thinning dominants are cut to favor promising trees in co-dominant or subordinate crown positions. A practice that may resemble either harvest type involves the removal of trees with more regard for species than canopy class. This practice is used in the tropics in places where only a few trees per hectare may be merchantable.

Geometric thinning is the removal or destruction of all trees in a regular pattern, usually in lines or nonlinear strips (Figure 3.1). This type of thinning is most often used as an expeditious way to reduce density in intensively managed young plantations, although it is also used in older, less-intensively managed stands where growth has stagnated and canopy differentiation has not occurred (Smith et al., 1997). In practice, it is common for more than one of the above thinning systems to be combined because of multiple management goals or the relatively high cost of each entry. Thus, the possibility of significant removals from all canopy classes should be allowed in the measurement of thinning activities.

Salvage

Salvage cuts are used to extract wood products from stands that have been injured by insects, fire, disease, or some other disturbance. Salvage harvests are often aggressively pursued by industrial forest landowners because of their need to recover the economic value of the dead trees. However, salvage is less common by public agencies, which are often charged to manage forests for both economic and non-economic values. Accessibility also influences the likelihood of salvage cuts; trees have a finite window of merchantability after mortality, and there often is not enough time to extend the infrastructure necessary for salvage.

Salvage cuts are different from the other types of harvest in that the harvested trees' photosynthetic contribution to canopy reflectance has either ended or been diminished prior to removal. This makes it difficult to detect a salvage thinning as an event separate from the initial disturbance. While new forest roads in a stand following a disturbance may be an indication of harvesting, many salvage operations are conducted by helicopter (Donovan, 2004), and others use existing road networks. Because of the fundamental difficulty in separating salvage cuts from the mortality resulting from the disturbances that precede them, salvage cuts are not considered in the following sections.

DATA CONSIDERATIONS FOR HARVEST DETECTION

Coops et al. (Chapter 2, this volume) describe major issues involved with using remotely sensed data to detect forest disturbances. With Chapter 2 as background, this section focuses on considerations of remotely sensed data that are specific to the detection and characterization of harvests. As described in the preceding section, harvest types vary in tangible ways, including: the stratum of the canopy that is removed, the vigor of remaining trees, the expected response of the understory, and the patchiness of removal. Since all of these factors can influence the reflective properties of a stand, this section makes use of previously described silvicultural distinctions as a framework for understanding the spatial, temporal, and spectral resolution issues surrounding the remote detection of harvest.

Spatial Properties

The spatial resolution required of the data supporting harvest mapping depends largely on the dimensions of the forest changes to be mapped. Woodcock and Strahler (1987) suggested that spatial resolution should approximately match the spatial scale of the features of interest. If cells are much larger than the features to be detected, the spectral signal of the features will be averaged with and perhaps lost in the "noise" of spectrally dissimilar neighboring areas (Lefsky and Cohen, 2003). If spatial resolution is significantly finer than features of interest, cell values will display the reflective properties not of the features themselves but of their physical components, resulting in unnecessary within-feature spectral variation.

The most commonly used remotely sensed data for harvest mapping have come from sensors such as Landsat and SPOT (Système pour l'Observation de la Terre) that have functional resolutions of 10–100 m (e.g., Alves et al., 1999; Cohen et al., 2002; Franklin et al., 2000; Heikkonen and Varjö, 2004; Jin and Sader, 2005; Sader et al., 2003; Saksa et al., 2003; Varjö, 1996; Woodcock et al., 2001). SAR (synthetic aperture radar) data have also been resampled to this resolution for harvest mapping (Ranson et al., 2003). This grain size is fine enough in relation to the size of most harvest units that the ratio of boundary pixels influenced by exterior conditions is relatively small compared to the number of interior pixels. However, this resolution does not allow identification of individual or small groups of trees that have been either cut or retained through the harvest process. While the presence of these trees may be inferred through modeling (e.g., Collins and Woodcock, 1996; Healey et al., 2006), the spatial averaging that occurs in the Landsat/SPOT range of resolution precludes explicit mapping of the removal and retention patterns that distinguish the various harvest practices described in this chapter.

A variety of sensors, including digital frame camera platforms such as Airborne Data Acquisition and Registration (ADAR) and satellite-based systems like IKONOS and QuickBird have the ability to detect removal of large individual trees (Clark et al., 2004; Read et al., 2003). Although high-resolution sensors have been little used in regional harvest detection, they represent a potential means to better distinguish cuts that target co-dominant trees (i.e., crown thinning and selective harvest) from those that target typically broader dominant trees (i.e., selective thinning and high-grading) and those that remove no canopy trees (low thinning). The low thinning that is obscured from passive optical systems by the overstory could potentially be directly measured with canopy-penetrating technologies such as interferometric synthetic aperture radar and laser altimetry (LIDAR). However, to our knowledge, no work on this approach has been published, however.

Coarser spatial resolution data, including data from the AVHRR (advanced very high resolution radiometer) and MODIS (moderate resolution imaging spectroradiometer) platforms, have been used to map land cover changes across large areas

(Lambin and Ehrlich, 1997), but individual disturbances can be difficult to isolate at that scale (Ehrlich et al., 1997). Zhan et al. (2002), using 250-m MODIS data, were able to detect large-scale natural disturbances such as fire and flooding with relatively high accuracy. They found mapping of small-scale harvests, however, to be more problematic. Potter et al. (2005) used time series of 8-km AVHRR data to identify sudden decreases in fraction of photosynthetically active radiation over 20 years in the Pacific Northwest. According to finer-scale maps produced with Landsat data, these events roughly corresponded to large wildfires and periods of accelerated harvests. For calibrating global carbon models, the purpose and scale for which it was designed, this algorithm produced satisfactorily detailed information about harvest levels.

For mapping individual harvests, however, the majority of harvest detection projects have used medium spatial resolution data (e.g., Landsat). Although the silvicultural distinctions that may be possible through the use of high spatial resolution imagery (e.g., IKONOS) would communicate a good deal about managerial intentions and the likely future stand development, the tradeoff discussed in Chapter 2 of this volume between spatial resolution and spatial extent, has thus far limited the role of such data in harvest detection.

Temporal Properties

The element of change in harvest mapping places particular emphasis on the temporal dimensions of the source data set. The remeasurement frequency must match the duration of the harvest signal, and measurements must be available that cover the time period of interest. Before discussing issues of temporal resolution, the relatively straightforward issue of temporal extent is mentioned. If digital source data is required for a period prior to the mid-1990s, the choice of platforms includes CORONA (operational from 1959 to 1972), Landsat (launched in 1972), AVHRR (launched in 1978), and SPOT (launched in 1987). This is not to suggest, however, that harvest detection must limit itself to historical data sources as it moves forward. For example, several harvest-mapping programs have successfully bridged the spectral and spatial differences between Landsat Multi-Spectral Scanner (MSS) and Landsat Thematic Mapper (TM imagery) (Alves et al., 1999; Cohen et al., 2002; Lunetta et al., 1998; Woodcock et al., 2001). Rigina (2003) combined declassified CORONA panchromatic high-resolution imagery from 1964 with both Landsat and Indian Remote Sensing 1C panchromatic imagery from 1996 to study forest decline and disturbance in Russia. The same objectives could also be accomplished with digitized historical aerial photos. Further cross-platform efforts should be expected as the constellation of remote sensing platforms evolves.

For the sake of simplicity, comparative discussions of temporal resolution in this section assume a Landsat-like data source of medium spatial and spectral resolution. A distinction must be made between the temporal resolution of a particular sensor (i.e., potential overpass frequency) and the temporal resolution of the data set assembled for a harvest detection project. While it may be beneficial to possess a temporally dense sample of remotely sensed data, particularly to the extent that it allows separation of harvest and phenological change (Coppin et al., 2004), the cost of acquiring and coregistering imagery can strictly limit the number of dates considered (e.g., Lunetta et al., 1998). There are also cases in which very high temporal resolution can be counterproductive. If a harvest is carried out over months or years as a series of light removals, the spectral signal of what in aggregate may be a significant harvest could be rendered imperceptible when spread out over several monitoring periods. This scenario is most likely in areas where shelterwood retention harvests are common.

More common, though, is the concern that if the monitoring interval is too long, harvest signal will be lost or diluted because of postharvest canopy regrowth. This regrowth can take the form of regeneration of desired species and their competitors in the case of regeneration harvests, or it can take the form of canopy expansion in trees remaining after a thinning. Regeneration harvests generally produce a spectral signal that may be long-lasting (i.e., several years) but is also dynamic. Although the trees that regenerate following these harvests often grow quickly because of newly abundant site resources, the time required for this regeneration to appear and then the rate at which it grows can be highly variable across a landscape (Yang, 2004). Ecosystem productivity may play a role in how quickly harvest signal decays (Healey et al., 2005) and so may ownership-dependent variables such as pre- and postharvest site preparation. A survey of some of the many projects focused on detection of clearcuts (Banner and Ahern, 1995; Cohen et al., 2002; Hayes and Sader, 2001; Masek, 2005; Saksa et al., 2003) revealed remeasurement intervals ranging between 2 and 14 years. As a general rule, if harvest is to be mapped in terms of intensity and not just occurrence, fairly high temporal resolution will be required to minimize the degenerative effects of growth on the harvest signal.

Although no study based solely on remotely sensed data has characterized harvests according to the silvicultural framework outlined, a few have partial harvests as a separate class. Franklin et al. (2000), working in New Brunswick, and Fischer and Levien (2001) in California were able to map harvests with fairly high accuracies into broad categories of intensity using Landsat TM data separated by five years. Working in Maine, Jin and Sader (2005) found that while five-year monitoring intervals produced clearcut maps nearly as accurate as those using two-year intervals, annual or biennial imagery was preferable for characterizing less-intensive harvests. Healey et al. (2006) used two-year intervals in Washington to produce continuous estimates of cover loss and basal area removal. In choosing the remeasurement frequency for a harvest-mapping project, consideration should be given to the stability of the harvest signal in relation to the level of detail required by the change detection process (recall Figure 2.5). Signal decay is influenced both by regional harvest practices and local revegetation rates. If fine distinctions between harvest levels are to be mapped or if light removals must be detected, then more frequent data collection will be needed.

Spectral Properties

For the detection of harvests, the ideal remotely sensed data will sample the areas of the electromagnetic spectrum that best separate the forest canopy from whatever mix of soil and vegetation is exposed when trees are removed. The better the contrast

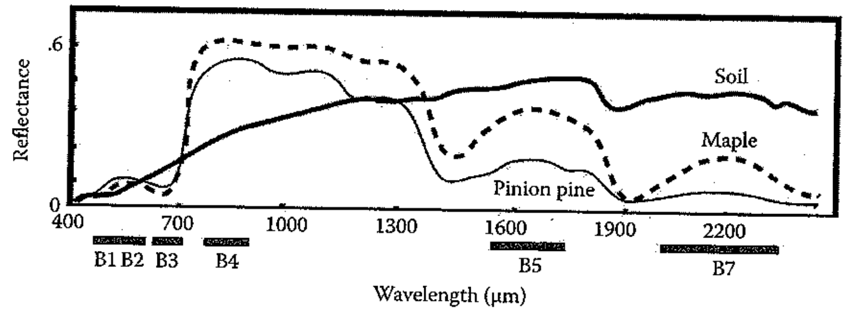

FIGURE 3.2 Reflectance patterns of three physical components of a study scene. (Adapted from Lefsky, M.A. and Cohen, W.B., in M. Wulder and S. Franklin, Eds., *Methods and Applications for Remote Sensing: Concepts and Case Studies* (pp. 13–46), Kluwer Academic Publishers, Norwell, MA, 2003, with kind permission of Springer Science and Business Media.) Wavelengths measured by the Landsat TM bands (B1-B5, B7) are also shown.

in reflectance between disturbed and undisturbed forest, the more easily canopy removal can be measured. Factors that influence the spectral contrast between canopy and background include species composition, soil properties, shadow patterns, and canopy density. The ability to predict wavelengths at which reflectance from canopy and background are most different can help not only in the choice of satellite, but also in targeting useful bands.

Figure 3.2 presents end member reflectances of soil, conifer needles, and deciduous leaves from a local spectral library (modified from Lefsky and Cohen, 2003). For simplicity, if these three elements were the only reflective components of a scene, then the general response in any spectral region could be predicted for a given harvest practice. Since the three components in Figure 3.2 differ little at the 400- to 530-nm range, a relatively slight response would be expected if a harvest was to realign their relative weights in the composite spectral response. Alternately, a substantial signal would be observed in the 1600-nm region if a harvest removed the conifer component, leaving an equal mix of hardwoods and soil reflectance. If the background were made up purely of soil, then the harvest signal at this range would be even more pronounced.

Familiarity with the spectral effects of the harvest practices to be encountered can inform the choice of the spectral characteristics of a project's source data. The above scenario is, of course, a simplification of the factors affecting reflectance. Factors like logging slash, skid trails, herbaceous composition, species shifts, and shadow can make the interpretation process more complex (Danson and Curran, 1993; Franklin et al., 2000; Nilson et al., 2001; Olsson, 1994). A number of harvest mapping projects have focused on the contrast between reflectance in the visible range (particularly in the red), which is strongly absorbed by vegetation, and the near infrared, which is not (e.g., Banner and Lynham, 1981; Hayes and Sader, 2001; Miller et al., 1978; Singh, 1989; Zhan et al., 2002). The majority of these studies utilized transformations such as the normalized difference vegetation index to accentuate the red/near-infrared contrast.

Strong evidence has emerged that the shortwave infrared (SWIR) portion of the spectrum contains information that greatly improves characterization of changes in forest structure (Skole and Tucker, 1993; Cohen and Goward, 2004; Collins and Woodcock, 1996; Lu et al., 2004; Skakun et al., 2003; Williams and Nelson, 1986). As can be seen in Figure 3.2, significant separation exists between soil and vegetation reflectance in the SWIR range (B5 and B7), so reducing the fractional contribution of vegetation through harvest should result in higher reflectance in this range. This is generally the case, while visible reflectance typically also increases, and near-infrared reflectance decreases (Franklin et al., 2000). Figure 3.3a illustrates this pattern as observed in a study of partial harvest in Washington (Healey et al., 2006). The similarity between these data and results from Finland presented by Olsson (1994) suggest a relatively consistent response among regions. The wetness index of the tasseled cap transformation (Crist and Cicone, 1984), which is a contrast between the sum of the visible/near-infrared bands and the sum of the SWIR bands, is commonly used with Landsat data to amplify the changes in SWIR in harvest detection (Cohen and Goward, 2004; Franklin et al., 2000). Healey et al. (2006) found a strong relationship between wetness change and degree of basal area removal (Figure 3.3b).

Although the wetness transformation is orthogonal to the other tasseled cap indices (Crist and Cicone, 1984), the results presented in Figure 3.3b clearly suggest a strong negative correlation between brightness and wetness in forest change space. This putative correlation was used by Healey et al. (2005) to reduce tasseled cap space to a single axis called the disturbance index, which is oriented in the presumed direction of increasing canopy removal. Jin and Sader (2005) mapped harvests using the normalized difference moisture index (NDMI), which contrasts near infrared and SWIR. NDMI-derived maps were similar in accuracy to maps produced with tasseled cap wetness, and NDMI can be used with sensors for which no tasseled cap transformation has been developed.

The above studies were carried out with sensors of low-to-medium spectral resolution. Little use has thus far been made of hyperspectral imagery to map harvests. Likewise, although a number of groups are currently investigating the potential for using LIDAR in harvest detection, little has been published in this area (Lefsky and Cohen, 2003). A good deal of work has been done with SAR in the microwave portion of the spectrum to detect clearcuts and conversion cuts. Intensity of backscattering in this range can be significantly different in forests and clearings, and this difference can be used to map canopy openings (Drieman, 1994; Ranson et al., 2003; Saatchi et al., 1997; Yatabe and Leckie, 1995). Coherence of the return signal phase between two dates can also be used to identify harvests (Antikidis et al., 1998; Smith and Askne, 1997, 2001; Wegmüller and Werner, 1995), although care must be taken in image acquisition because radar imagery can be sensitive to seasonal (Cihlar et al., 1992) and weather differences (Smith and Askne, 2001). Texture images have also been derived from SAR data and have been used to aid in the identification of clearcuts (Luckman et al., 1998; Sanden and Hoekman, 1999). Measurements of partial harvests have not yet been made with SAR, however with different wavelengths of microwave energy able to penetrate to different depths of the canopy (Jet Propulsion Laboratory, 1986; Treuhaft et al., 2004), there exists the

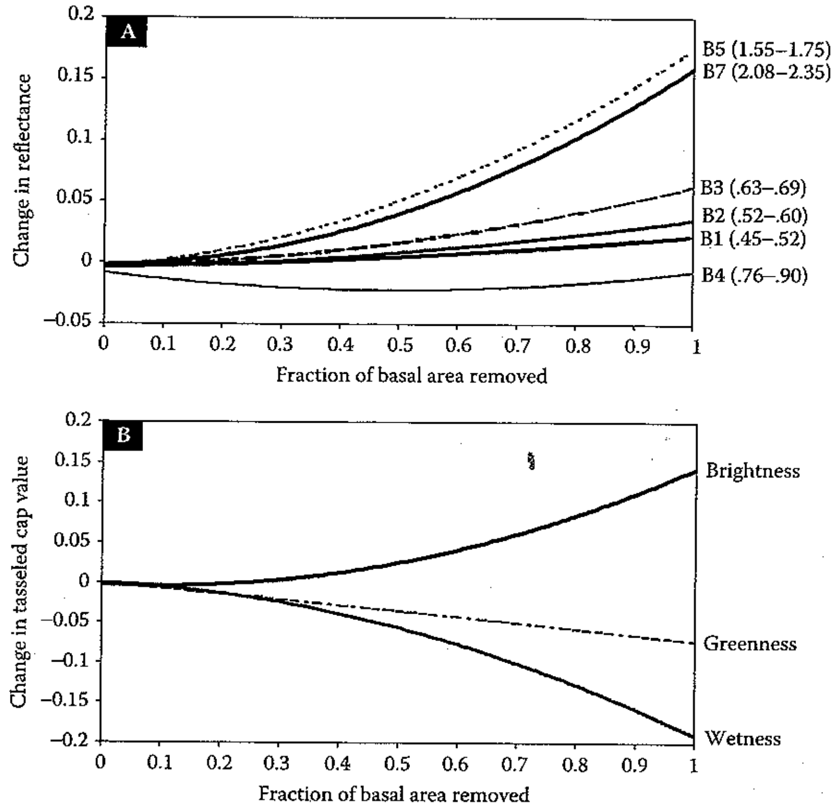

FIGURE 3.3 Changes in Landsat reflectance values (a) and tasseled cap indices (b) associated with a range of basal area removals in central Washington. Basal area removal was inferred from stump data combined with harvest permit records. Digital counts of Landsat imagery corresponding to pre- and postharvest conditions were converted to ground reflectance units using the COST model described by Chavez (1996). Tasseled cap values were calculated using coefficients described by Crist and Cicone (1984). Landsat bands are displayed with associated wavelengths (in micrometers).

possibility of directly monitoring understory removals in stands in which the overstory is unaltered.

HARVEST METRICS

Coppin et al. (2004) suggested that any approach to digital change detection includes both a change extraction algorithm and a set of rules for separating or labeling meaningful levels of change. These authors described ten categories of change extraction routines, the most common of which were postclassification comparison (*delta classification*), multidate composite analysis, univariate image differencing, image ratioing, and change vector analysis. Milne (1988), Singh (1989), and Coops et al. (Chapter 2, this volume) also discussed and categorized methods for detecting ecological change. The use of any of these processes depends on the identification of a measurement variable that is specifically relevant to the type of change studied.

Considerable variation exists in how harvests are labeled. The first section of this chapter described a hierarchy of harvest types based on silvicultural principles. However, vernacular usage of many silvicultural terms is sometimes inconsistent. Since the mapping process requires the identification of an attribute that is at least internally consistent, care should be taken in choosing a harvest measure that is both useful and unambiguous. This section focuses on how the effects of harvest may be conceptualized in a mapping context. It should be emphasized that all of the harvest variables to be discussed can be mapped with a range of levels of precision, depending on the quality of the supporting data and the ability of the chosen change extraction algorithm to identify necessary distinctions. Levels of precision may include simple detection of the presence/absence of harvest activity, classification of harvests into two or more categories, or estimating harvest effects as a continuous variable.

There are at least three ways that the changes resulting from harvest may be mapped: in terms of the general intensity of canopy removal; as a change in a particular biophysical variable (e.g., biomass, cover, density); or by silvicultural harvest type. The majority of published harvest detection studies identified harvests that remove most of the canopy; these harvests are alternately called forest cutovers (Hall et al., 1989), clearcuts (Banner and Ahern, 1995), and stand-replacing harvests (Cohen et al., 2002). Such studies typically create a binary map identifying cuts from specific time periods. Many such efforts lack either the reference data or the image spatial resolution to ensure a consistent silvicultural definition of the cuts that are mapped. However, any retention harvests that may be loosely classified as clearings are likely to resemble clearcuts in terms of percentage canopy removal. Thus, in practice, the attribute of interest in these maps is general canopy reduction. As a broad measure of harvest level, this attribute has value both in the monitoring of industrial management activities (Sader and Winne, 1992) and as an element of large-scale ecological processes (Cohen et al., 1996).

More specific quantification of the canopy removal resulting from harvest requires a more precise framework for describing the canopy. Potentially appropriate variables may include leaf area index, canopy cover, volume, basal area, and biomass. A variety of studies have shown these variables to be appropriate for characterization with remotely sensed data under certain conditions (Franklin, 2001; Hall et al., 1998; Lu et al., 2004; Mallinis et al., 2004; Steininger, 2000). Healey et al. (2006) estimated the changes in basal area and canopy cover over a range of harvest intensities using Landsat imagery, sample plots, and historical aerial photos. In addition to increasing the precision with which harvests can be labeled, modeling changes in specific biophysical variables expresses harvest in terms that may be of direct use in updating stand inventory information.

Another way to describe harvest is by silvicultural practice. As mentioned, limitations in the horizontal and vertical spatial resolution of many types of remotely sensed data realistically preclude direct monitoring of many of the silvicultural distinctions between harvest types. However, Franklin et al. (2000) and Sader et al. (2003) used harvest records to enable distinction between clearcuts and partial cuts.

In both studies, "clearcut" classes met the silvicultural definition of a clearcut, while all other harvests, including practices such as geometric harvesting and selective thinning, were grouped into the "partial cut" class. The advantage of considering harvests in silvicultural terms, particularly if individual partial cut practices can be identified, is that different practices may reflect different managerial priorities and create a richer context from which to project future developments.

As partial harvests become more common because of efforts to reduce fuel loads (Brown et al., 2004) and as a result of changing forest practice laws (Sader et al., 2003), the need for more nuanced harvest information will increase. Different metrics of forest removal have the ability to emphasize different structural or silvicultural elements of harvest. Therefore, the decision of how to label and differentiate harvest types should be based on monitoring needs and should be integrated into the design of the overall change detection approach.

CASE STUDY IN HARVEST DETECTION: STAND-REPLACING HARVESTS IN THE PACIFIC NORTHWEST (UNITED STATES)

Background and Methods

The Northwest Forest Plan (the plan) was a 1994 amendment to the management plans of federal forestlands within the range of the spotted owl (*Strix occidentalis caurina*) in California, Oregon, and Washington. The aim of this plan was to balance the maintenance and restoration of older forest ecosystems with a predictable and sustainable level of harvest. Effectiveness monitoring was an important component of the plan, and separate monitoring programs were established to assess, among other plan outcomes, trends in old-growth forest ecosystems, habitat of spotted owls and marbled murrelets (*Brachyramphus marmoratus*), and the socioeconomic status of people in timber-dependent towns. Although a system of remeasured inventory plots has provided regionwide estimates of the net loss or gain of different forest types in the region, a spatially explicit record of significant disturbances was needed to assess changes to older forests and to owl habitat (Lint, 2005; Moeur et al., 2005). Furthermore, historical context was desired regarding harvest rates both before and after the plan was enacted.

The monitoring strategy designed to meet these needs included the mapping of stand-replacing harvests and fires in Oregon and Washington from 1972 to 2002 in approximately four-year intervals using composite analysis with Landsat MSS, TM, and Enhanced Thematic Mapper Plus (ETM +) data. Change detection in California was approached differently (Levien et al., 2002) and is not discussed here. Methods used in Oregon and Washington were chosen in consideration of project needs. Landsat imagery was used as it satisfied the need for historical data and because its moderate spatial resolution struck a balance between a large study area (14.5 million Ha; see Figure 3.4) and the need for accurate spatial referencing of disturbances. Also, the spectral resolution of the Landsat satellites, particularly TM and ETM+, which provide SWIR information, has been useful in several vegetation mapping projects in the region (Cohen and Goward, 2004). The mapping interval minimized

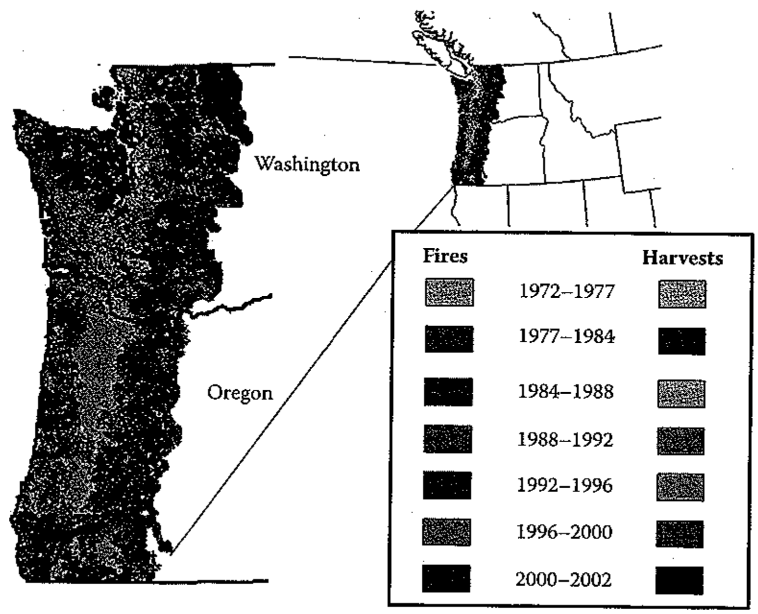

FIGURE 3.4 (See color insert following page 146.) Map of stand-replacing harvests and fires within the range of the northern spotted owl in Oregon and Washington from 1972 to 2002.

image acquisition and processing costs while offering sufficient temporal resolution for the detection of clearings in the Pacific Northwest (Cohen et al., 1998).

The stand-replacing harvest attribute (the detection of fires is not discussed here) met the study's need to identify cuttings that removed all or nearly all of a stand's trees. It should be noted that, silvicultural definitions notwithstanding, the stand-replacing designation used here does not apply to gradual shelterwood cuts that leave a large percentage of resident trees. In fact, harvests leaving a large canopy component (partial harvests) were intentionally excluded from the map. The identification and labeling of harvested pixels was accomplished through the use of composite analysis, a process by which a multitemporal "stack" of image data is classified to identify relevant changes. Accurate cross-date spatial coregistration is essential in this process (Coppin and Bauer, 1996), and an automated tie-point program (Kennedy and Cohen, 2003) was used to carefully coregister imagery. Other data preparation, detailed by Healey et al. (in review) included masking out nonforest areas using a land cover layer prepared for the plan area (Weyermann and Fassnacht, 2000) and subsetting Landsat images along general ecosystem boundaries to reduce ecological variation in the spectral signal. Composite analysis was chosen because it was judged to be an accurate and efficient means of isolating pixels displaying multitemporal spectral signatures consistent with stand-replacing harvest (Cohen and Fiorella, 1998). Supervised classification, by which spectral properties of disturbed and undisturbed pixels are identified in advance, was chosen for this analysis. An informal study (Figure 3.5) indicated that such a process, when used with a maximum likelihood classifier, is more efficient at isolating clearcut pixels than

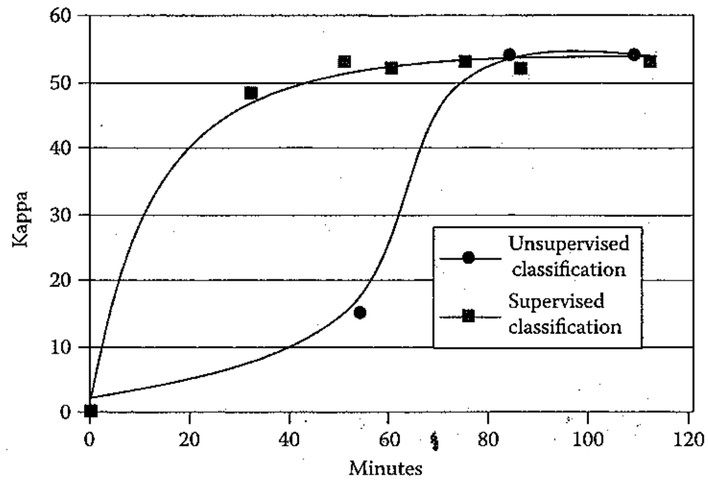

FIGURE 3.5 Pilot study of efficiency of composite analysis using unsupervised and supervised classification to detect stand-replacing harvests. Both approaches were applied in a 500,000-Ha study area in central Washington to create maps identifying stand-replacing harvests over two 4-year intervals using tasseled cap-transformed Landsat TM data. Resulting maps were evaluated against the Landsat imagery, allowing iterative adjustment of classification parameters (indicated by individual points). Kappa accuracy of successive maps was measured against hand-digitized disturbance maps and plotted over processing time. Reported times do not reflect preprocessing procedures that were common to both approaches.

unsupervised classification. Unsupervised classification relies on analyst interpretation of feature space clusters and can be time consuming when clusters are not well aligned with the boundaries of desired classes.

Prior to composite analysis, the tasseled cap transformation was performed on the Landsat data for data reduction and feature emphasis (see Data Considerations section). A further transformation, called the disturbance index (DI), was performed on the tasseled cap indices to produce a single band per image/date. This index quantifies the degree to which a pixel fits a profile that is presumed to match the position of clearcuts in tasseled cap space. Specifically, pixels with high tasseled cap brightness and low tasseled cap greenness and wetness values have high DI values. Details of the transformation can be found in the work of Healey et al. (2005). Pixels that move suddenly from low to high DI values are identified by the classifier as having been disturbed. Composite analysis in different regions has shown DI-transformed imagery to produce results comparable to tasseled cap-transformed data (Healey et al., 2005). Further, reduction to a single band allows visualization of multitemporal imagery in a single computer monitor. Figure 3.6 shows a three-date display of DI imagery that can be interpreted using additive color logic to identify the timing of each harvest. This ready identification of the date of each clearing facilitated the selection of training polygons for supervised composite analysis. Postprocessing of the Oregon and Washington disturbance map included the mosaicking of all of the mapped segments together and the removal of all mapped cuts

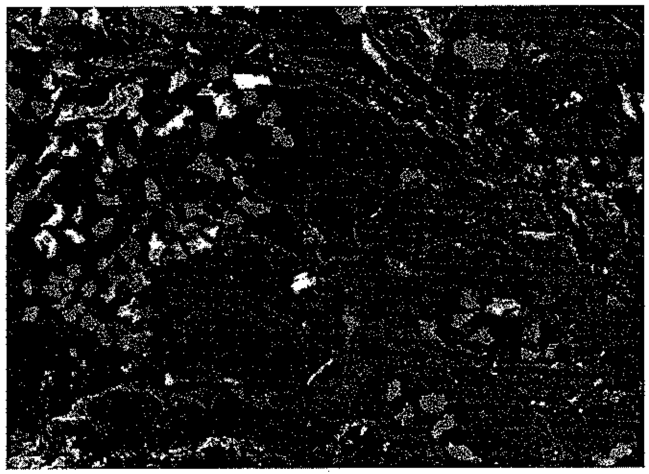

FIGURE 3.6 (See color insert following page 146.) Three dates of DI as viewed in a typical red-green-blue (RGB) monitor. The first date (1988) is plotted in the red color gun, the second (1992) in the green, and the third (1996) in the blue. Using the assumption that DI is high in disturbed areas, additive color logic can be used to interpret this multitemporal image. Cyan-colored areas are high in both the second and third dates, suggesting a disturbance between the first and second dates. Blue pixels have a high DI only in the third date, indicating the occurrence of a disturbance between the second and third dates. Reddish colors indicate stands disturbed prior to the first date that are becoming revegetated by the second and third dates.

and "islands" of retained trees that were less than 2 Ha in size. The latter measure was intended to remove small areas of error introduced by spatial misregistration.

Results and Analyses

The map that was created through this process (Figure 3.4) displayed stand-replacing harvests larger than 2 Ha and identified the time period in which they occurred. Map error was assessed at approximately 2500 randomly selected points through a sampling strategy described by Cohen et al. (2002). Error rates (88.9% overall accuracy with a kappa coefficient of 0.83), reported by Healey et al. (2006), were acceptable for the analyses described in the next paragraph. In general, the earlier dates, which were mapped with lower spatial resolution Landsat MSS data, were less accurate than TM-mapped dates. On the pixel level, most errors resulted from either spatial misregistration or confusion of partial harvests with stand-replacing harvests.

Three types of analyses were performed with the map in support of the plan's vegetation monitoring program. First, the map was considered in conjunction with a variety of geographical information system layers to identify harvest trends over ecological provinces, ownership categories, and federal land use designations. Figure 3.7 shows harvest trends by ownership. Notable in the graph is the dramatic reduction in harvest on federal Forest Service and Bureau of Land Management lands during the time that has coincided with the Northwest Forest Plan (Moeur et al., 2005). The second type of analysis focused on the average size of harvest units for each

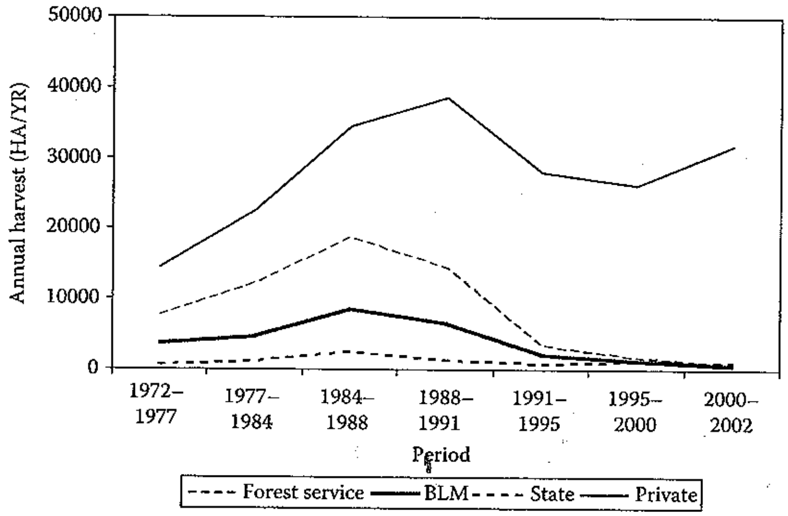

FIGURE 3.7 Annual area of stand-replacing harvest by major forestland owners in the Oregon portion of the Northwest Forest Plan area.

ownership over time; in general, stand-replacing harvests on private land were larger than those on public land over all time periods (Healey et al., in review). Finally, the map was combined with circa 1996 maps of older forests and owl and murrelet habitat to identify recent changes in those resources. Summaries of these analyses can be found in the work of Moeur et al. (2005) and Lint (2005).

CONCLUSIONS

Forest harvests can be measured in several ways. A large number of projects have focused on mapping clearcut-like operations that remove a majority of trees. Harvests can also be mapped according to silvicultural labels or as changes in specific biophysical variables. Each of these metrics can be mapped with a range of specificity, demanding more or less spatial, temporal, and spectral resolution of the supporting remotely sensed data set. Independent of the choice of detection algorithm, familiarity with expected harvest practices can facilitate interpretation of remotely sensed data for harvest mapping.

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