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Monitoring U.S. Forest Dynamics with Landsat

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12.1 Introduction: U.S. Forest Dynamics in the Global Context

Forest dynamics in the United States differ substantially from those in the developing world and thus present unique monitoring requirements. While deforestation and conversion to semipermanent agriculture dominate tropical forest dynamics, the area of forest land in the United States has remained fairly constant for the last 50–60 years (Birdsey and Lewis 2003). Although the United States experienced rapid deforestation during the eighteenth and nineteenth centuries, much of the eastern clearing regrew during the twentieth century as marginal agricultural land was abandoned.

Recent inventory reports indicate very small rates of net forest cover change in recent decades, with the area of U.S. forests increasing by slightly more than one-tenth of 1% per year since 1987 (Smith et al. 2009).

Rather than land use conversion, forest dynamics in the United States are dominated by harvest, fire, and other temporary disturbance processes. These processes do not change the net area of forest land use, but dramatically affect the forest age structure, landscape ecology, carbon balance, and habitat suitability. It is thought that about 1.4% of forest land area is affected by harvest each year in the United States, and another 0.4% is affected by fire (Smith et al. 2009; U.S. EPA 2011). However, these disturbance rates are not static. Changes in forest management as well as recent climate change may be affecting contemporary disturbance rates relative to historic norms (e.g., van Mantgem et al. 2009).

The United States relies on its national forest inventory for domestic and international reporting of forest change. The U.S. Forest Inventory and Analysis (FIA) program collects data on a set of over 300,000 plots across the United States, with one plot per every ~2,430 ha. A range of attributes are collected in addition to stand volume, including stand age, species composition, and management practice. The key aspect of this design-based inventory is that the sampling error associated with any variable is well constrained, and thus robust estimates across broad areas can be made with known sampling uncertainty. Plots are remeasured on a 5- to 10-year cycle, depending on the state. Like other nations, the United States reports national forest carbon dynamics as part of the United Nations Framework Convention on Climate Change (UNFCCC). In this case, inventory data from the FIA and other agencies are collated and reported by the U.S. Environmental Protection Agency (EPA).

While the FIA is well suited for estimating national forest statistics, it is not designed to accurately capture local dynamics due to disturbance and other rare events. For example, while a difference between a 1% per year and 2% per year disturbance rate is truly significant from an ecological point of view, a very large number of random samples is needed to distinguish those two rates with any level of precision. Given the FIA plot spacing, this implies that disturbance rates cannot be accurately characterized below the scale of 100s of kilometers.

The desire for consistent, geospatial information on forest disturbance and conversion has invigorated the application of Landsat-type remote sensing technology for forest monitoring in the United States. This work builds on a significant legacy that dates back to the launch of Landsat-1 in 1972 (Cohen and Goward 2004). Early efforts at basic land cover mapping identified forests as a unique spectral region (the so-called badge of trees in red-near-IR space) that enabled reliable single-image mapping of forest cover. Studies during the 1980s and 1990s established the opportunity to use multirate Landsat imagery to characterize forest conversion, harvest, burned area, and insect damage. Recent increases in computing power, coupled with the gradual opening of the Landsat archive for free distribution,

have resulted in researchers undertaking increasingly ambitious programs in large-area forest dynamics monitoring. Here we describe several of these efforts, focusing on national-scale work in the United States.

12.2 Overall Forest Disturbance: LEDAPS and NAFD Projects

The North American Carbon Program (NACP) is an ongoing interagency effort within the United States to constrain the North American carbon budget, improve process understanding, and forecast future scenarios. The NACP Science Strategy recognized at the outset that ecosystem disturbance was a critical but poorly known parameter required for more accurate assessments of ecosystem carbon flux. Accordingly, two Landsat-based projects were organized during 2004–2005 in order to meet NACP modeling needs (Goward et al. 2008).

The LEDAPS (Landsat Ecosystem Disturbance Adaptive Processing System) project was based on traditional two-date change detection, but across very broad spatial scales (Masek et al. 2008). The main objective was to map stand-clearing disturbance (primarily fire and clearcut harvest) across all forested land in the conterminous United States and Canada. At the start of the project, the Landsat archive was not yet free. Instead, the project chose to use the Global Land Survey (GLS) preprocessed Landsat data sets (Tucker et al. 2004). The GLS data sets consist of cloud-free imagery for epochs centered on 1975, 1990, 2000, 2005, and 2010. For the LEDAPS project, the focus was on estimating forest disturbance between 1990 and 2000.

The LEDAPS processing approach focused on establishing accurate surface reflectance values from each image, and then using those data to perform two-date change detection using a tasseled cap disturbance index. Considerable work went into establishing a sensor calibration and atmospheric correction approach suitable for use with the GLS data sets, including revising the Landsat-5 calibration look-up table based on invariant desert targets and adjusting the calibration of the older GLS data sets to reflect the new table. The development of a stand-alone atmospheric correction code for Landsat was a significant side benefit of the project.

Beyond sensor calibration, a number of other challenges were encountered during the disturbance mapping. First, the 10-year (1990–2000) change-detection span caused stands disturbed during the early part of the epoch to exhibit significant regrowth, resulting in high omission errors of 40%–50%. This issue has previously been documented (Jin and Sader 2005) and suggests that change detection on closer to annual timesteps is more appropriate for most forest monitoring applications. Statistical summaries reported in Masek et al. (2008) compensated for this issue by adjusting rates by the difference between omission and commission errors. Second, many

of the GLS images from the 1990 and 2000 data sets were acquired during senescent parts of the growing season, confusing the change-detection approach. These images were replaced with new imagery purchased from U.S. Geological Survey (USGS).

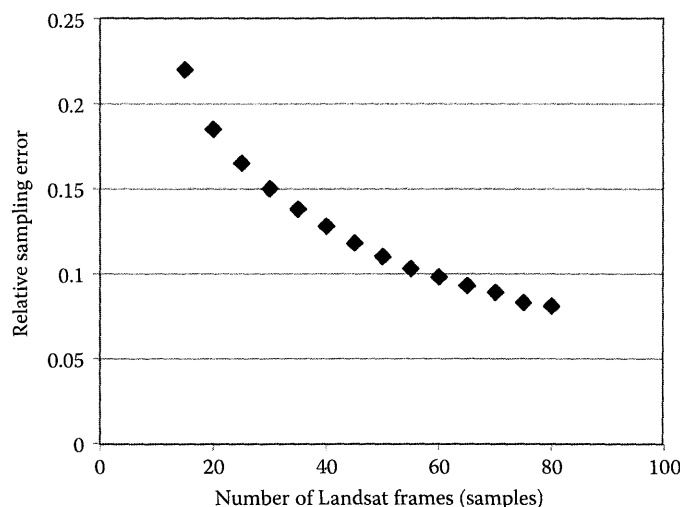
The results of the continental mapping indicated that 2.3 Mha/year of U.S. forest land was affected by stand-clearing disturbance during the 1990s, representing a fractional disturbance rate of 0.9% per year, or an equivalent "turnover" period of 110 years. The highest disturbance rates were found in areas with significant harvest activity, including the southeastern United States, Maine/Quebec, and the Pacific Northwest. Rates in the mid-Atlantic and New England were lower, reflecting both less overall harvest activity and greater prevalence of partial harvest, which could not be reliably detected using the LEDAPS measurement period.

While LEDAPS focused on wall-to-wall assessment of disturbance at a coarse temporal timestep, the North American Forest Dynamics (NAFD) project took an alternate path: characterizing disturbance using a sparse geographic sample of Landsat imagery at annual temporal resolution (Goward et al. 2008). The NAFD originally began with a sample of 23 Landsat frames across the United States and later expanded to a set of 50 frames. For each frame, a set of biennial (later annual) Landsat imagery was assembled, and time-series analysis was used to map forest disturbance.

The NAFD geographic sample was designed to support robust characterization of national disturbance rates (eastern and western United States as separate estimates) based on an unequal probability sampling design. This sampling design was based on selecting across strata for U.S. forest types (Ruefenacht et al. 2008) while also accommodating the inclusion of fixed sites from earlier phases of the work. The decision to increase the number of samples from 23 to 50 reflected the desire to reduce the national sampling error to less than 10% (Figure 12.1).

Aligned with several other recent studies (Kennedy et al. 2007), the NAFD disturbance-mapping effort relied on detecting anomalies in per-pixel spectral time series. The specific algorithm, the vegetation change tracker (VCT; Huang et al. 2010), used a Z-score procedure to normalize each image in the time series by dividing by the standard deviation of reflectance values for a set of undisturbed forest pixels. Anomalies were then mapped based on significant, long-lasting excursions from the time series (Huang et al. 2010). Both the year of disturbance and the spectral magnitude were included in the final products (Figure 12.2). It should be noted that the annual timestep used in the algorithm allows partial disturbances (such as thinning, partial harvest, and mortality from storms and insects) to be tracked.

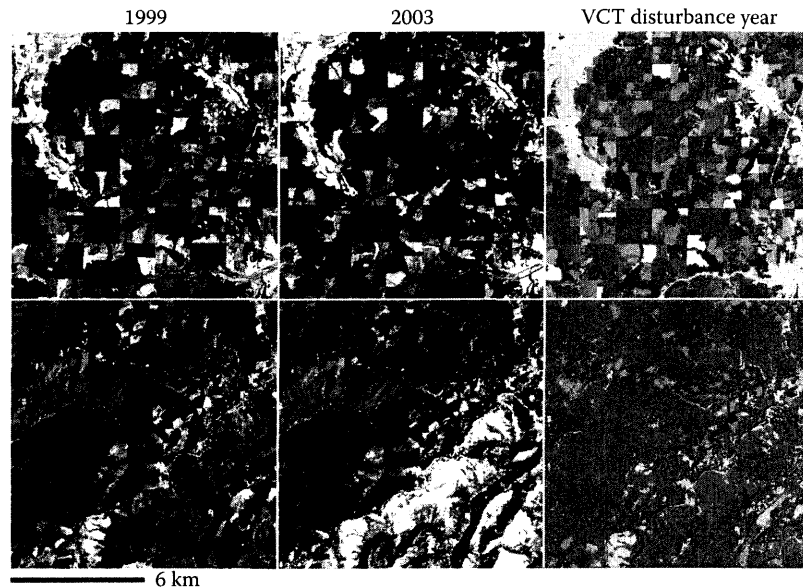
Overall, the sampling results indicate about 1.1% of forest area disturbed each year in the United States during the 1985–2005 period. Although

**FIGURE 12.1**

Relative error of U.S. national disturbance rate estimates as a function of the number of Landsat frames (path/row locations) used in the geographic sample, estimated from initial drafts of sample-level disturbance rate for all years from 1985 to 2005. Relative error is the proportional difference between the estimated value from the sample and the unknown true value, subject to a 90% confidence interval. (Analysis courtesy of Robert Kennedy, Oregon State University, Corvallis, OR.)

disturbance rates in the western United States are dominated by fire and insect damage, while rates in the east are dominated by harvest, overall disturbance rates were not significantly different between the west and east. However, there were significant year-to-year differences. For example, disturbance rates in the western United States increased to 1.5% per year during the early 2000s as a result of extremely active fire years. There were also significant geographic differences in disturbance rate within individual forest type strata.

The fact that disturbance rates vary significantly in both space and time raises doubts that sampling approaches can adequately characterize the disturbance regime at continental scales. The assumption behind the NAFD sampling approach was that disturbance rate was fundamentally a function of forest type (or at least that forest type could act as a proxy for the controlling factors). This assumption has not been borne out by the scene-by-scene results. As a result, the latest phase of the NAFD project has abandoned the geographic sampling scheme and switched to an ambitious "wall-to-wall" characterization of annual disturbance rate for the entire conterminous United States. This effort will require processing in excess of 20,000 Landsat images and is taking advantage of

**FIGURE 12.2**

(See color insert.) Examples of NAFD disturbance mapping from southern Oregon (Landsat path 46, row 30). Top row: RGB imagery (bands 7, 5, 3) and VCT disturbance maps for an area of active harvest; bottom row: RGB imagery and disturbance map for the northern edge of the 2002 Biscuit Fire. The VCT maps show permanent forest (green), permanent nonforest (gray), and the year of mapped disturbance from 1985 to 2009 (other colors).

the NASA Earth Exchange (NEX) parallel computing environment at the NASA Ames Research Center.

12.3 Operational Fire Monitoring: MTBS and LANDFIRE

Although wildfire is a primary disturbance agent within the United States, the area affected by forest fire has not been well characterized. The National Interagency Fire Center (NIFC) maintains a database of major wildfires, but does not consistently discriminate between forest fires and other wildfires (e.g., brushfire or grassfire). Furthermore, the area recorded is based on an external perimeter of each large fire, rather than the actual area affected by burning. Two operational projects, Monitoring Trends in Burn Severity (MTBS) and LANDFIRE, are using Landsat remote sensing to improve burned area and fire risk monitoring.

A collaboration between the USGS and the U.S. Forest Service (USFS), the MTBS project is seeking to supplement the NIFC database with accurate

information on U.S. fire area and burn severity (Eidenshink et al. 2007). The primary goal of MTBS is to provide sufficient information to quantify interannual variability in U.S. burned area and to understand the extent to which forest management and environmental factors may be influencing longer term trends in fire.

MTBS has acquired preburn and postburn (1 year after fire) Landsat imagery for all major wildfires within the United States since 1984, as identified from government databases (Eidenshink et al. 2007). Fires larger than 1,000 acres in the western United States and larger than 500 acres in the eastern United States are considered in the project. The normalized burn ratio (NBR) spectral index is calculated for the image pair bracketing a major fire, and a difference (dNBR) image is generated by subtracting the pre- and postfire NBR values. The NBR metric takes advantage of the fact that recent fires leave considerable char, ash, and mineral soil, which tend to be relatively bright in the shortwave infrared compared to the near-infrared. While the NBR metric has been questioned as a suitable proxy for overall fire severity in Boreal ecosystems (Hoy et al. 2008), it has also been shown to be highly correlated with canopy damage (Hoy et al. 2008) and overall fire impact in temperate ecosystems (Cocke et al. 2005). MTBS data are available online (<http://www.mtbs.gov>) in a variety of formats, including geospatial products and statistical summaries of annual burned area by region and ecosystem.

LANDFIRE is a multipartner project producing 30 m Landsat-based maps of vegetation, fuel, fire regimes, and ecological departure from historical conditions across the United States (Rollins 2009). Leadership is shared by the wildland fire management programs of the USDA Forest Service and the U.S. Department of the Interior. LANDFIRE's maps are widely used for both fire management and ecological modeling. Circa-2000 imagery was used to produce LANDFIRE's original maps, and a combination of approaches is used to track subsequent disturbances so that maps may be kept up to date (Vogelmann et al. 2011).

The initial updating mechanism involved intersecting LANDFIRE maps with the fire events mapped by the MTBS project (described above). This approach has recently been augmented with management activities (conducted mostly on federal lands), which have been recorded in a spatial database. Because a more automated process was needed for incorporating the effects of disturbance events, LANDFIRE has recently done extensive work with the VCT algorithm described earlier under the activities of the NAFD project. An estimated 30,000 Landsat images will ultimately be used to map disturbance extent and magnitude across the conterminous United States (Vogelmann et al. 2011).

Because the cause, or type, of a disturbance plays an important role in its effect upon fuel conditions, cause attribution is underway for LANDFIRE's VCT maps. This process makes use of the MTBS data to some extent, but it also currently involves a good deal of manual classification. Current

LANDFIRE disturbance-mapping efforts focus on the Landsat TM era, but extension into the MSS era is a longer term goal, as is continued mapping into the future.

12.4 Forest Cover Conversion: Trends, NLCD, and C-CAP

While the emphasis of the preceding projects has been on characterizing forest disturbance rates, permanent conversion of forest cover remains an ongoing process within the United States. The trend during most of the twentieth century was toward increased forest cover via agricultural abandonment. However, increased urban and suburban growth during the last 50 years has altered this pattern in some areas. The projects discussed here have viewed forest change from the perspective of land cover conversion and have used Landsat-based change detection to separate gross forest change (including harvest and other disturbances) from the lower rates of long-term land cover and land use conversion.

The USGS Trends project began in the late-1990s using a random sample of Landsat subsets, stratified by EPA ecoregion, to characterize both regional and national trends in land cover (Loveland et al. 2002). Each Landsat subset was either 10,000 or 40,000 ha (e.g., 10 km × 10 km or 20 km × 20 km). For each subset, images were collected for the years 1973, 1980, 1986, 1992, and 2000 and manually classified into a series of land use classes, as well as two classes representing recent mechanical disturbance (harvest) and fire. As in the NAFD project, the sampling framework allowed sampling uncertainty to be quantified. The overall goals were to provide estimates of gross change with an uncertainty of <1% at an 85% confidence interval (Drummond and Loveland 2010).

The Trends data set has been used widely for studies of land use conversion (Drummond and Loveland 2010), ecosystem carbon (Liu et al. 2006), biodiversity, and surface energy balance (Barnes and Roy 2008). For the eastern United States, Drummond and Loveland (2010) assessed both gross and net forest cover change using the Trends data and concluded that eastern forests experienced 142,000 ha/year of net forest conversion during the 1973–2000 period due mostly to urbanization, surface mining, and reservoir construction. Gross forest change rates were 2.5 times higher and mostly reflected harvest activities.

The National Land Cover Database (NLCD) project, coordinated by the USGS EROS Data Center, has produced wall-to-wall U.S. maps of land cover for 1992, 2001, and 2006. While NLCD image selection criteria, classification methods, and target classes have evolved over the course of the project, significant efforts have been made to ensure interpretable maps of change among different land covers (Xian et al. 2009; Fry et al. 2011). Changes between

the 1991 and 2001 products were identified through a "retrofitting" process, which involved standardization of classification schemes, and a sequence of decision tree-based operations that first identified and then labeled land cover transitions. Differences in Landsat ratio-based indices were primary predictors for this process.

Likewise, (different) Landsat-based indices were used in the 2001–2006 change identification process, which used complex heuristic-based threshold rules to identify changed pixels and to indicate whether changed pixels were losing or gaining biomass. This change-detection process, multi-index integrated change analysis (MIICA; Fry et al. 2011), produced change maps that were intersected with the land cover product from 2001 (considered to be the base year) in nondeveloped areas to generate the 2006 cover product.

Mapping projects such as the NLCD's are an important complement to inventory estimates of forest change. In the United States, the FIA provides ground-acquired estimates of land use not available from automated satellite processes, and it provides a design-based error structure for its estimates of net change of forest area. However, the FIA does not measure gross transitions to and from other cover types. NLCD can specify that its estimate of a net loss of 16,720 km² of evergreen forest cover, for example, is the result of a 36,000 km² gross loss and a 19,000 km² gross gain (Fry et al. 2011). As discussed earlier, maps also provide a picture of change at much more localized scales than is achievable with a simple random sample.

The NOAA's Coastal Change Analysis Program (C-CAP) maintains a nationally standardized database of landcover and landcover change in coastal regions of the country (Dobson et al. 1995). Thematic classes, including those for forests, are consistent with those used in the NLCD (described earlier), and C-CAP is actually the source of the NLCD data in coastal zones. Landsat has been the basis for classification and change detection for C-CAP national maps using imagery from 1996, 2001, 2006, and 2011 (in progress), as well as high-priority local analyses going back to the mid-1980s.

The 2001 cover map, produced from three dates of imagery collected by the MRLC (multiresolution land characteristics consortium), is considered the baseline product, and only those areas determined to have changed are reclassified in subsequent products (J. McCombs, NOAA, personal communication). For changes between 2001 and 2006, CCA (crosscorrelation analysis) was used to detect change using imagery from the two dates. Landcover transitions were estimated with classification and regression trees (CARTs). Change detection between 2006 and 2011 will be consistent with the multithreshold change vector analysis used by NLCD (Xian et al. 2009). Spatial data and customized summaries of C-CAP maps are freely available from the C-CAP Web site.*

* <http://www.csc.noaa.gov/digitalcoast/data/ccapregional/index.html>

12.5 Synthesis of U.S. Forest Dynamics

Given that several studies have used satellite data to quantify forest disturbance rates in the United States, how do these estimates compare with each other, and with inventory-based rates? Satellite-based estimates of disturbance rates are available in Masek et al. (2008), and via the MTBS data products (available online). In addition, Hansen et al. (2010) presented MODIS-based measures of gross forest loss that includes both disturbance and deforestation. Figure 12.3 shows a comparison among these estimates. We also show inventory-based estimates of harvest, fire, and insect damage from Smith et al. (2009) and U.S. EPA (2011) annualized for the 2000–2008 period. Finally, we also derived an annualized rate of “stand-clearing” disturbance from the FIA by taking the area of U.S. forests less than 20 years of age, and dividing by 20, under the assumption that a stand-clearing event should reset the measured stand age on the FIA plot.

The range of estimates shows an expected trend, with shorter remeasurement periods (e.g., the annual NAFD) and finer resolution (e.g., Landsat vs. MODIS),

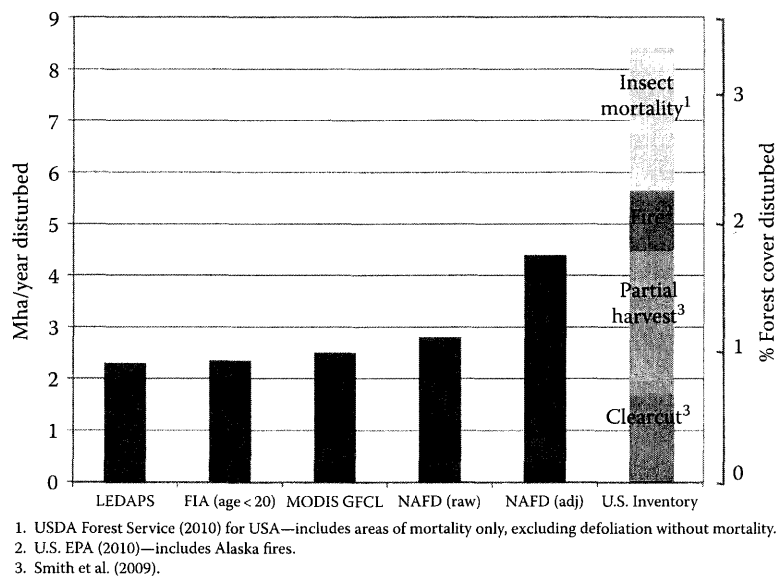


FIGURE 12.3

(See color insert.) Comparison of disturbance rates among satellite-based and inventory-based studies. LEDAPS (Masek et al. 2008) and NAFD (Kennedy et al. in preparation) are based on Landsat change detection. NAFD (adj) reflects compensation for net omission errors based on visual validation. MODIS GFCL is based on MODIS gross forest cover loss (GFCL) (Hansen et al. 2010). The FIA (age < 20) is based on equating the area of young forestland from the FIA with an annualized turnover rate. The percent forest cover values are based on the area of forest land in the “lower 48” conterminous United States (~250 Mha).

leading to more disturbances mapped and higher overall rates (Figure 12.3). The LEDAPS result of 0.9% per year corresponds closely to the FIA-derived stand-clearing rate (0.9% per year) and the gross loss derived from MODIS (1.0% per year). The ability of the NAFD annual data to capture some thinning and partial harvest likely explains the somewhat higher rates (1.1% per year). Further adjusting the NAFD rates for the net omission error of the products would increase these rates further, to about 1.5% per year.

All of these rates are significantly lower than what can be derived from inventory estimates alone (Smith et al. 2009; U.S. EPA 2010). This may reflect the difficulty in measuring minor disturbances using remote sensing, including selective harvest that does not significantly alter the forest canopy. Field- and satellite-based disturbance estimates may also differ in what they label "disturbance." The FIA's definition of disturbance includes "mortality and/or damage to 25 percent of all trees in a stand or 50 percent of an individual species' count" (FIA 2011). In addition to the canopy mortality targeted through remote sensing, this characterization certainly includes large areas affected by insects or storms, where sublethal damage may affect only a small fraction of the trees. Thus, discrepancies in Figure 12.3 may be due to both varying sensitivity and inconsistent definitions among data sources.

12.6 Looking Forward

The opening of the Landsat archive and advances in computing technology have paved the way for broader and more innovative applications of Landsat data for forest monitoring. These innovations include mapping at wider geographic scales (e.g., wall-to-wall national monitoring), the use of dense time series to better characterize intra- and interannual variability, and a greater sophistication in leveraging multiple data sources to attribute the origin of forest change as well as ecosystem consequences. Given that the Landsat archive is most complete within the United States, it is natural that many of these techniques are being pioneered for U.S. applications. However, given the increased global data collections implemented for Landsat-7 and the upcoming LDCM (Landsat Data Continuity Mission), these approaches could be applied to global monitoring as well.

12.6.1 Operational Monitoring of Forest Dynamics: LCMS

The Landscape Change Monitoring System (LCMS) is under development by a consortium of scientists, agencies, and projects engaged in remotely sensed change detection in the United States. Coordinated by the Forest Service and Department of Interior/USGS, LCMS is intended to be a hub around which

existing national change products such as those from MTBS and NLCD may be integrated and extended. The ideal change monitoring system would provide up-to-date and consistent information about the location, magnitude, and nature of vegetation changes on all land cover types across the country. The research- and agency-based monitoring efforts described in this chapter address different aspects of this ideal system, and several steps are being taken under LCMS to promote both integration of existing products and cooperation on the development of new products.

First, LCMS is conducting an independent needs assessment of the land management community. Acquired information about the type, precision, and frequency of needed land change information will guide development of new monitoring strategies. Many of the needed answers are likely to come from the combination of current resources. For instance, LANDFIRE is anticipating a more meaningful update of their fuel maps as fire records from the MTBS are augmented with more general all-disturbance mapping achieved through the VCT (Vogelmann et al. 2011). Similar benefits of product integration likely extend into processes such as carbon accounting, where disturbance emissions are strongly influenced by event type and magnitude.

Any new products developed by the LCMS to meet identified needs will likely depend heavily upon the Landsat archive and will draw upon the experience of participating partners. Like the MTBS project, the LCMS will follow a collaborative multiagency business model, with an emphasis upon meeting operational monitoring needs by producing consistently updated and validated products. The LCMS is expected to be deployed during 2013.

12.6.2 Hypertemporal and Near-Real-Time Change Detection

The use of dense image time series has pushed the “epoch length” (i.e., the time between images used for monitoring change) to shorter and shorter periods. Not surprisingly, the range of forest dynamics that can be assessed has expanded as well. While semidecadal time series are useful for monitoring net land cover change and stand-clearing disturbance (Jin and Sader 2002; Drummond and Loveland 2010; Masek et al. 2008), more subtle disturbances require annual image acquisition. Thus the algorithms proposed by Kennedy et al. (2007) and Huang et al. (2010) are capable of detecting significant thinning, partial harvest, and selective mortality from insects and disease. However, even these algorithms may not record subtle and short-lived degradation of the forest canopy due to insect defoliation, storm damage, and selective cutting.

A variety of approaches are being prototyped to obtain seasonal or even submonthly information from Landsat. The WELD (Web-Enabled Landsat Dataset) project at the University of South Dakota is using MODIS-style compositing to generate monthly and seasonal gridded composites

of Landsat-7 data. Zhu and Woodcock (in press) have proposed an approach to mapping forest disturbance by fitting per-pixel phenological curves using every available Landsat observation. These methods not only obtain greater sensitivity to short-term canopy changes, but by explicitly considering changes relative to observed phenology they minimize errors due to mismatches between annual image dates.

12.6.3 Integration of Landsat with Active RS for Biomass Change

Landsat data have proven robust for estimating the area affected by forest change processes. However, Landsat data have not proven as useful for forest volume or biomass estimation, except in conditions of sparse tree cover where volume can be directly related to canopy cover (Powell et al. 2010). There are, however, a variety of ways in which change area from Landsat can be combined with active remote sensing in order to better quantify "three-dimensional" changes in forest structure and biomass. Direct fusion between Light Detection and Ranging (LIDAR) and Landsat has been proposed to improve retrieval of biomass. Landsat imagery has also been proposed as a way to spatially interpolate LIDAR "samples" across the landscape using krigging techniques as well as a way to group LIDAR measurements based upon patterns of forest structure and disturbance. More recently, disturbance and age information derived from Landsat have been combined with LIDAR data to estimate postdisturbance carbon accumulation rates and to improve spatial interpolation of height (Li et al. 2011). In principle, similar work could be carried out using one-time biomass retrievals from radar (including interferometric SAR) combined with historical disturbance data from Landsat.

12.6.4 Ecological Impacts of Climate Change and Recovery Trajectories

The projects discussed here have focused mostly on quantifying the fraction of U.S. forest land disturbed and the fraction that reverts back to forest after disturbance. The spectral information of Landsat time-series data also offers important information on the *rate* at which ecosystems recover from disturbance. In one example, Schroeder et al. (2007) related postharvest Landsat spectral trajectories in the Pacific Northwest to increases in canopy cover deduced from air photos. The current phase of the NAFD project is extending this work by assessing rates of forest recovery for all recently disturbed patches in the United States.

One application for such approaches is to understand how ecosystem recovery may be responding to climate warming. A number of studies have suggested increased rates of forest decline in the southwestern United States due to prolonged drought (Williams et al. 2010), and van Mantgem et al. (2009) found evidence for increased rates of tree mortality throughout the western United States. Disturbance events (fire, insect outbreaks, and

disease) may be accelerated in climate-stressed forests, and successional pathways may be altered or slowed. Ultimately the 40+ year Landsat record will prove valuable for understanding the long-term shifts in forest composition and mortality associated with climate warming in the United States.

12.7 Conclusions

The application of Landsat remote sensing to the monitoring of U.S. forests has accelerated during the last decade. This trend reflects both the development of new algorithmic and computational approaches for dealing with large volumes of data and the opening of the Landsat archive for free distribution by the USGS. The projects discussed here represent large-scale mapping efforts that have sought to characterize U.S. forest dynamics during the Landsat era, including disturbance, recovery, and conversion.

Although the U.S. forest inventory will continue to provide our most robust national estimates of forest attributes, remote sensing is increasingly being called on to perform operational monitoring of forest and land cover change. The appropriate integration of geospatial information from remote sensing with forest attribute available from the FIA remains one of the significant challenges for the future. The k -nearest neighbor approach of assigning suites of FIA attribute data based on spectral properties has found acceptance within the USFS as it allows the statistical variance of the FIA-reported attributes to be "imported" to the geospatial products (McRoberts et al. 2002). Alternative approaches have sought instead to use statistical models to predict attributes from Landsat spectral data using the FIA attributes as training data (e.g., Powell et al. 2010) or to use Landsat-derived harvest maps to spatially distribute the FIA-recorded harvest volumes (Healey et al. 2009). Ultimately the extent to which remote sensing can support operational needs depends on the trade-off between measurement error and sampling error. Landsat remote sensing can record wall-to-wall dynamics, and thus has no sampling error, but may exhibit significant errors of omission and commission (measurement errors) depending on the attribute of interest.

The launch of LDCM in early 2013 will continue the Landsat legacy while providing a greater density of global acquisitions compared to Landsat-7. In addition, the ESA Sentinel-2 satellites will be launched during 2013–2014. Like Landsat, the Sentinel program has committed to open access for its archive. Taken together, the LDCM and Sentinel missions will provide an extremely rich source of global observations for the next decade. It is anticipated that many of the advances in the use of Landsat data described here, including time-series methods, will soon find global use.

About the Contributors

Jeffrey G. Masek is a research scientist in the Biospheric Sciences Laboratory at the NASA Goddard Space Flight Center. His research interests include mapping landcover change in temperate environments, application of advanced computing to remote sensing, and satellite remote sensing techniques. Dr. Masek currently serves as the Landsat project scientist at NASA. He received a BA in geology from Haverford College (1989) and a PhD in geological sciences from Cornell University (1994).

Sean P. Healey is a research ecologist who works for the FIA program at the U.S. Forest Service's Rocky Mountain Research Station. His interests include linking Landsat data to inventory records for the purpose of tracking forest carbon storage over time.

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