Measurement of Forest Disturbance and Re-growth With Landsat and FIA Data: Anticipated Benefits From FIA's Collaboration With NASA and University Partners

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Abstract. FIA (Forest Inventory and Analysis Program, U.S. Forest Service) has partnered with researchers from NASA (National Aeronautics and Space Administration), the University of Maryland, and other Forest Service units to identify disturbance patterns across the United States using FIA plot data and time series of Landsat satellite images. Spatially explicit predictions of biomass loss and gain from 1972 to 2002 will be produced in two-year intervals using 25 Landsat scenes distributed throughout the country. The map-based analyses that will be made possible through this collaboration will complement FIA's current ability to track disturbances at the county and state level.

Overview of the Collaboration

FIA has entered into a collaborative agreement with a diverse team of scientists for the purpose of using historical Landsat data to measure forest disturbance and re-growth since 1972. FIA analysts across the

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country are working with other Forest Service scientists and collaborators from NASA, the University of Maryland, and Oregon State University to create biennial maps of forest biomass change. Three stated goals for this project are:

1. To characterize disturbance regimes for forests across the U.S. and portions of Canada.
2. To evaluate the variability of post-disturbance forest re-growth.
3. To develop techniques that enable FIA analysts to study the disturbance history of any forested area in the country.

This collaboration has the potential to significantly improve FIA's capacity to monitor the forest changes resulting from disturbance. Historical Landsat imagery has been used to map the occurrence of several types of forest disturbances, including: harvest (e.g., Cohen et al. 2002, Healey et al. 2005, Sader 1995); fire (e.g., Cocke et al. 2005); insect activity (e.g., Skakun et al. 2003); and storm events (e.g., McMaster 2005). In addition to mapping the occurrence and extent of disturbances, a few studies have attempted to measure their effect, either in general classes of tree mortality (Franklin et al. 2000, Jin and Sader 2005, Skakun et al. 2003) or as continuous variables representing change in an element of forest structure (Collins and Woodcock 1996, Healey et al. in press [a], Olsson 1994). The scope and precision of the maps to be produced through the current collaboration are unique. Biennial estimates of biomass loss and gain will be produced for areas across the continental United States and portions of Canada at the resolution of the Landsat pixel (~30m). This production of highly specific (in time, space, and degree) estimates of change over an area of almost 1 million square kilometers is only possible through the combined expertise of the assembled partners. The following section describes the relevant capacities of each of the partners and the contributions they are expected to make. The final section of this paper contains a discussion of the possible benefits to FIA of the products and techniques resulting from this effort.

Collaborators

NASA

LEDAPS (Landsat Ecosystem Disturbance Adaptive Processing System) is a NASA-funded program based at the Goddard Space Flight Center. The goal of this program (http://ledaps.nascom.nasa.gov/ledaps/ledaps_NorthAmerica.html) is to map forest disturbance and re-growth across the North American continent using three dates of Landsat imagery (1975, 1990, 2000). In meeting the significant logistical challenges of processing such a large number of images, LEDAPS has developed several automated algorithms for critical tasks such as: removal of atmospheric effects, radiometric normalization, orthorectification, and disturbance detection (table 1). These algorithms will support not only the processing of the imagery needed in this project, but will also, once validated, be available to FIA for use in other projects.

The LEDAPS continent-wide disturbance maps will be available by mid-2006. It is likely that because of the decadal sampling interval for these maps, a portion of disturbances will not be detected. Vegetation re-growth following a disturbance can mask the disturbance's spectral signal if the sampling frequency is low (Healey et al. 2005, Jin and Sader 2005). Through the current collaboration, disturbance rates will be identified in more than 25 Landsat scenes across the country with imagery acquired at two-year intervals from 1972 to the present using methods discussed below. These scenes will be chosen in a national-scale sampling framework so that the resultant disturbance maps may be used in concert with the LEDAPS product to improve national-level estimates of forest disturbance rates.

FIA

The national network of inventory plots maintained by FIA has a sampling intensity of at least one plot per 6000 acres (approximately 1400 plots per Landsat scene). In addition to measuring biometric characteristics such as biomass and basal area at each plot, FIA records the likely cause and estimated year of forest disturbances occurring at each plot between measurements. FIA's plot data may be used in several ways to train and validate satellite-based forest change detection algorithms. A plot may be viewed categorically according to its binary FIA plot-level disturbance attribute, in which case it could be used to support the mapping of the location, but not the intensity, of disturbances. If a plot has been measured both before and after the identified disturbance, then the degree of damage may be assessed in terms of change in a stand attribute such as live volume or biomass. In this case, predictive models of disturbance intensity may be built using the relationship between the degree of measured physical change and the spectral differences seen in pre- and post-disturbance imagery. Plots that have not been re-visited may still support efforts to map disturbance intensity. Measurements of attributes such as biomass from any date may be associated with contemporaneous imagery, and, if there is adequate radiometric normalization among images across time, a date-invariant predictive spectral model for that attribute may be produced. If that model is uniformly applied to normalized imagery from different dates, differences in predicted conditions may contain significant information about the intensity of local disturbances (Healey et al. in press [a]).

FIA scientists, having long had access to the spatial coordinates of the nation's largest forest inventory, have made important strides both in the modeling of biophysical variables using remotely sensed data (e.g. Blackard et al. 2004, Frescino et al. 2001, Lister et al. 2004, McRoberts et al. 2002, Moisen and Frescino 2002) and in the assessment of those models (Czaplewski and Patterson 2001, Edwards et al. 1998, Patterson and Williams 2003). In this respect, it is likely that FIA personnel will be instrumental both in interpreting information from FIA plot records and in modeling that information. FIA analysts will also be instrumental at the local level in helping to identify the causes of mapped disturbances. Finally, FIA will have a role in communicating the results of this project as disturbance trends are included in regional and national reports.

Other Forest Service and University Partners

While FIA's scientists have used satellite imagery and plot data to map forest conditions across large areas, the program has little experience in mapping forest changes. In contrast, other Forest Service collaborators and those from the University of Maryland and Oregon State University have a good deal of experience in developing (Cohen et al. 1998, Huang et al. 2000, Powell 2004), testing (Cohen and Fiorella 1998, Healey et al. 2005), and applying (Cohen et al. 2002) Landsat-based change detection algorithms. Because of this experience, Forest Service and university partners will have a leading role in developing methods for mapping change. As stated earlier, these methods will use historical Landsat imagery to both measure the intensity of forest disturbances and plot the re-growth of disturbed stands. Illustrating the degree to which this project will draw upon the strengths of all collaborators, the change detection algorithms developed by the Forest Service and university researchers will rely on both the mass pre-processing techniques designed by NASA personnel and the plot data and modeling techniques provided by FIA.

Benefits to FIA

This collaboration will greatly increase the spatial precision with which FIA can characterize disturbance across the United States. FIA's sample-based estimates of forest conditions typically are made at the county or state level to assure the consideration of a statistically adequate number of plots. Although the estimation of forest attributes at the county level using FIA plot data is statistically straightforward, it precludes more spatially explicit analyses. This project will produce estimates of forest change at the scale of the Landsat pixel (~30 m), permitting fine-scale analyses of disturbances such as harvests, fires, and wind events that are not possible using the sample-based paradigm. Study of the spatial patterns of forest recovery will likewise be possible. This section will describe several potential applications of this project's change products that may be of use to FIA.

Harvest Detection

The basic products resulting from this project will be spatially explicit biennial estimates of biomass loss or gain within approximately 25 Landsat scenes. In order to translate these pixel-scale predictions into maps of disturbance, likely causes of each predicted disturbance will have to be identified. This process will likely focus on spatially contiguous patches of pixels displaying abrupt drops in estimated biomass.

Assignment of disturbance type may be automated using rules regarding the size, shape, spatial complexity, or texture of each patch (e.g., Cohen et al. 2002). Formulation of these rules will have to be made in consultation with FIA analysts and other local experts. Once the sources of individual disturbances are identified, spatial and temporal trends in harvests and other types of disturbance may be conducted.

Harvest is a significant cause of forest disturbance in many managed landscapes. Harvests that remove most or all of the trees in a stand have been mapped using Landsat imagery with relatively high accuracy (e.g., Cohen et al. 2002, Hall et al. 1989, Sader and Winne 1992). Several projects have also suggested the potential for the use of historical Landsat imagery to map partial harvests (Collins and Woodcock 1996, Olsson 1994, Sader et al. 2003). Landsat's short-wave infrared bands may be particularly useful in modeling the degree of canopy removal involved with a harvest (Healey et al. in press [a], Olsson 1994).

The production of spatially and temporally explicit maps of disturbance will allow FIA to augment its current timber output records. It will be possible to summarize harvest trends since 1972 by any combination of geographic variables, including: landowner, forest type, topography, or climate. For example, in a study supporting the monitoring component of the Northwest Forest Plan, Healey et al. (in press [b]) reported trends in clearcut harvesting for both federal and non-federal landowners in Oregon and Washington from 1972 to 2002 (fig. 1). The study showed that while non-federal forest owners continued to harvest at relatively high levels during the 1990s (the period coinciding with the Forest Plan), clearcutting of federal forests virtually stopped.

It is technically possible to create similar estimates of harvest by geographic variables using only FIA data since many of these variables are stored as plot characteristics. However, satellite-based estimates have at least three advantages. First, while FIA survey protocols and designs may have changed over the last 30 years, the continuity of the Landsat series since 1972 will allow relatively uniform measurement of disturbance in all time periods. Second, the specificity of plot-based estimates of harvest levels is limited by the conditions represented in the sample; harvest levels by a particular type of owner on particular slopes may only be estimated if a sufficient number of plots share those conditions. Lastly, disturbance maps resulting from this project may also be used to support purely spatial analyses for which sample-based methods are poorly suited. Healey et al. (in press [b]) looked at the size of clearcuts across time and owners (fig. 2), showing that federal forest administrators have consistently used clearcuts that are approximately half the size of non-federal owners. FIA plot data alone could not support this type of study. Other spatial attributes of harvests that may be of interest to FIA are: proximity to streams or population centers, spatial aggregation, and edge ratio. Thus, while FIA currently has the capacity to study harvest levels at the county or state level, the use of plot and Landsat data to create harvest maps will provide significant insight into how harvests are distributed across the landscape.

Fire Mapping

The Forest Service, through its Remote Sensing Applications Center (RSAC), currently supports two large-scale fire monitoring programs. Burned Area Reflectance Classification (BARC) maps are produced at RSAC for many forest fires using pre- and post-fire Landsat images. These maps categorize reflectance differences associated with fires, and these differences are then considered along with ancillary data to produce categorical maps of fire severity. These maps are not created for all fires, however, and do not produce an explicit estimate of forest lost. RSAC's other fire-monitoring program is the MODIS Active Fire Mapping Program, a collaboration with NASA Goddard, the University of Maryland, the National Interagency Fire Center, and the Missoula Fire Sciences Lab. This project identifies likely areas of fire activity using the thermal band from the MODIS instruments on the Terra and Aqua satellites. An effort is underway to further classify these active fire maps into fire severity classes. This classification may then be used in conjunction with data from FIA plots within each severity class to create rapid characterizations of the forest types affected by each level of fire severity.

The current Landsat-based project will complement the MODIS-based efforts in that although fire loss estimates will not be as immediate, they will have greater spatial resolution and they will be in the form of discrete predictions of biomass reduction at the pixel level. Additionally, maps will be available for fires occurring in the pre-MODIS era. The information implicit in these maps regarding the spatial distribution of fire effects may have several applications. LANDFIRE, a collaboration between the Forest Service and several other federal and private partners (www.landfire.gov), is creating maps of fuel conditions in the West using FIA data to train Landsat imagery. Fire intensity maps from the current project may be used to update LANDFIRE fuel layers. Maps of fires and other types of disturbance may likewise be used to update habitat maps (e.g., Lint et al. 2005). Since fires can create conditions favorable for some forest pathogens (Gara 1988), maps of fire damage may also be of use in guiding forest health monitoring activities.

Storm Damage Assessment

Hurricanes and other storms can cause widespread forest damage. Storm damage, however, may be localized; differential mortality rates may result from topography, stand structure, or other factors (Millward and Kraft 2004). Although FIA currently has the capacity to estimate volume loss at the county or multi-county level, it has no way to monitor local storm effects. Spatially explicit estimates of storm damage may provide insight into storm risk at the stand level, particularly in relation to local topography. Going forward, it may also be possible to use post-storm imagery in a "rapid response" mode. In areas where change detection algorithms have already been trained with plot data and historical Landsat imagery, obtaining forest change estimates would require only the normalization of a post-storm image and the application of the existing algorithm. Although ephemeral storm effects such as standing water may somewhat reduce the accuracy of damage estimates obtained immediately after a storm, such estimates may nevertheless have value in pinpointing areas of highest damage. This information may be used to direct salvage crews or damage assessment surveys. At least two of the 25 Landsat scenes to be processed through this project depict major storm-affected areas (1989's Hurricane Hugo in South Carolina and the 1999 Boundary Waters wind event in Minnesota). There is substantial FIA plot data from both before and after each of these storms, allowing assessment of this project's estimates of storm damage.

Post-Disturbance Recovery

Just as this project's estimates of biomass over time may be of use in identifying disturbances, the same estimates may allow measurement of the rate of subsequent biomass accumulation. Successional recovery following disturbance can be a highly variable process, both within and across ecosystems (Yang et al. 2005). The consequences of slow recovery after a disturbance may include erosion (Agee 1993) and the delay of timber production. Spatially explicit recovery information, like spatial disturbance information, may be used to complement FIA plot-based estimates. Historical recovery maps may be used to update fuel and habitat maps, and they may be considered with other geographic variables to create context-dependent models of recovery. Such models may be useful to managers considering the need for or likely success of active recovery efforts following large-scale disturbances such as fires or storms. The temporal resolution of the biennial Landsat imagery used in this project may be a particular benefit in the monitoring of post-disturbance stand dynamics. The five- or 10-year remeasurement intervals used by FIA may be less suited than biennial Landsat imagery to characterizing the potentially rapid changes (Oliver and Larson 1996) occurring after a disturbance. Thus, though FIA plot-based estimates may be used to estimate recovery rates at the county or state level, Landsat-based maps of forest recovery may add detail to our understanding of how recovery is spatially and temporally distributed.

Summary

This collaboration represents an opportunity for FIA to greatly expand the spatial information that it can provide to stakeholders and clients. An approach to forest change detection is being developed specifically to take advantage of the existing FIA database. The intrinsically spatial information resulting from this approach will complement the program's current ability to make area-based estimates of disturbance. Several applications of this spatial information in the monitoring of harvests, fires, storms, and re-growth have been suggested in this paper. The disturbance histories of 25 sample areas across the country are now being processed using Landsat imagery and FIA data. When these initial analyses have been completed, the change detection algorithm, the critical image processing tools developed by the LEDAPS program, and the maps of disturbance and re-growth will be available to FIA for future studies.

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Tables

Table 1.   Relevant processing algorithms under development by LEDAPS.

Algorithm name	Description	Current status
lndcal	Landsat-5 and Landsat-7 calibration and conversion to top-of-atmosphere reflectance	Operational
lndsr	Aerosol retrieval, atmospheric correction, conversion to surface reflectance	Operational / still in testing
lndcsm	Create cloud/shadow/snow mask	Prototype exists
lndreg	Precision image-to-image matching via GCPs and orthorectification	Operational / still in testing
lnddm	Disturbance mapping using Disturbance Index (Healey et al. 2005)	Operational / still in testing
lndcom	Direct surface reflectance compositing across multiple acquisitions without BRDF adjustment	Prototype exists

Figure Captions

Figure 1. Harvest rates in western Oregon and Washington on Forest Service (FS), Bureau of Land Management (BLM), and non-federal federal lands, 1972-2002. Shown is the annualized percentage of all forestland harvested using clearcut methods. Data from Healey et al. (in press [b]).

Figure 2. Mean patch size of clearcut harvest units on Forest Service (FS), Bureau of Land Management (BLM), and non-federal lands in western Oregon and Washington, 1972-2002. Data from Healey et al. (in press [b]).

Figures

Figure 1.

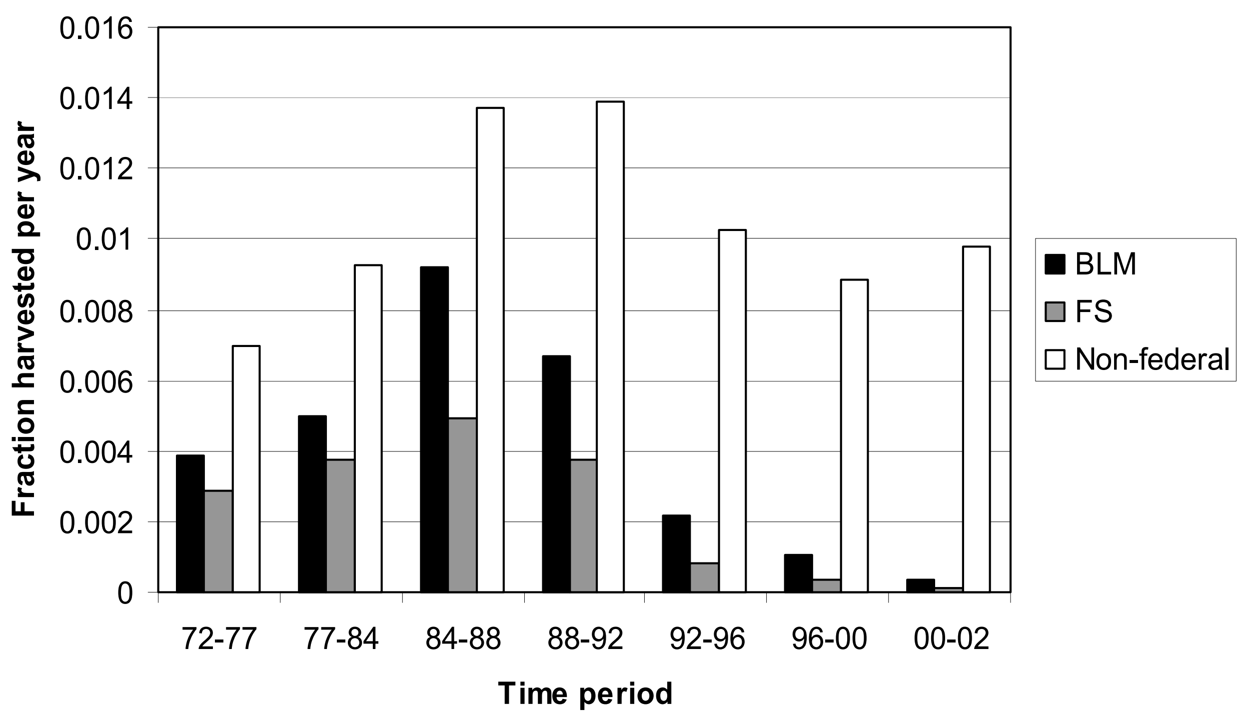
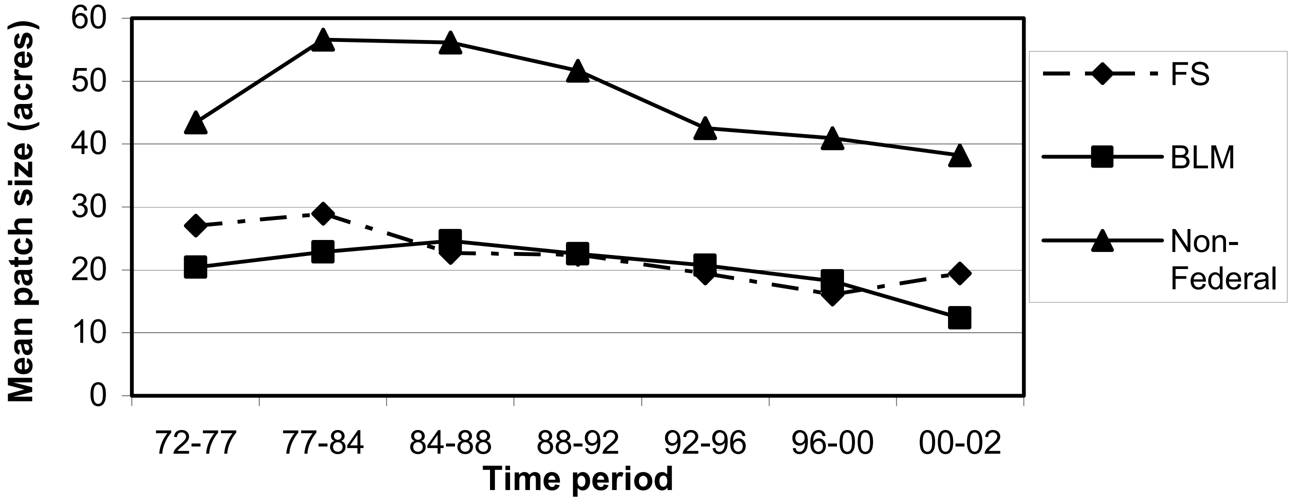


Figure 2.



Mean patch size (acres)
60
50
40
30
20
10
0
72-77
77-84
84-88
88-92
92-96
96-00
00-02
Time period
FS
BLM
Non-Federal