

# APPLICATIONS OF SATELLITE-DERIVED DISTURBANCE INFORMATION IN SUPPORT OF SUSTAINABLE FOREST MANAGEMENT

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## ABSTRACT

The need for current information about the effects of fires, harvest, and storms is evident in many areas of sustainable forest management. While there are several potential sources of this information, each source has its limitations. Generally speaking, the statistical rigor associated with traditional forest sampling is an important asset in any monitoring effort. However, the act of sampling implies that spatial patterns below the level of the estimation unit are ignored. Disturbance information derived from remote sensing is spatially explicit at the local level. This spatially explicit data, which can be validated at the plot level with traditional forest survey information if it is available, can support analyses related to the spatial orientation and context of disturbances as they occur across the landscape. Thus, remote sensing provides a credible and systematic complement to more traditional means of forest monitoring.

**Keywords:** Remote Sensing, Disturbance, Harvest, Management, Prioritization

## 1 THE ROLE OF REMOTE SENSING IN MONITORING FOREST DISTURBANCE

The decisions and planning involved with sustainable forest management require accurate and appropriate monitoring. Understanding the effects of disturbance on forest condition is particularly important; disturbances can cause abrupt changes in many attributes, including carbon and timber stocks, wildlife habitat, and water quality. Forest managers have at their disposal a number of tools for monitoring forest disturbance, including: sample-based estimation, spatial or tabular management records, aerial sketch maps (hand-drawn records of disturbance), and change detection using sequential remotely sensed data. It is important to understand the strengths and weaknesses of each method when choosing one for a monitoring program (see Table 1).

Over sufficiently sampled estimation units, systematically distributed ground measurements can be used to provide unbiased estimates of the occurrence and effects of forest disturbance. However, sample-based methods do not easily capture spatial attributes of disturbance such as contiguity, proximity, and patch size and shape (Healey et al., 2007). If tracking these attributes is a priority, or if synoptic monitoring is required (to update vegetation maps, for example), remotely sensed measurements may be needed. While

management records may document the spatial orientation of all activities on the land of a particular manager, these records rarely include the effects of natural disturbances, and their conventions, completeness, and availability vary greatly across the landscape. Aerial sketch maps are less bound by ownership issues, but the information they convey is limited to what can be seen briefly from an aircraft.

**Table 1.** Sources of disturbance information (leftmost column) vary in ways that affect their usefulness in different contexts. Information sources may display particular benefits either consistently (“+”) or under certain circumstances (“+/-”).

|                    | Well-understood precision | Consistent methods | Spatially Explicit | Universally Available |
|--------------------|---------------------------|--------------------|--------------------|-----------------------|
| Plot Network       | +                         | +                  |                    | +/-                   |
| Management Records |                           |                    | +                  |                       |
| Aerial Sketch Maps |                           | +/-                | +                  |                       |
| Remote Sensing     |                           | +                  | +                  | +                     |

Sources of data to support remotely sensed disturbance mapping range from aerial photography to sequentially acquired satellite imagery. The

Landsat series of satellites, operational since 1972, have been the workhorse platform for forest change detection (Cohen and Goward, 2004), but other passive (e.g. Zhan et al., 2002) and some active (e.g. Smith and Askne, 1997) sensors have also been used extensively. While remotely sensed data may be interpreted manually, the digital nature of satellite imagery enables a wide array of automated techniques (see surveys by: Coppin and Bauer, 1996; Gong and Xu, 2003).

This paper describes three scenarios in which remote sensing may contribute information to forest managers that is unavailable through other means. These examples highlight the advantages of being able to monitor the entire landscape in a spatially explicit way that is consistent across time and space.

## **2 UNIQUE BENEFITS OF REMOTE SENSING**

While the statistical framework that underpins traditional forest inventories is a critical asset, there are some spatial information needs in forest management that sampling the forest on the ground does not meet. This section discusses three of these needs: spatial orientation, spatial context, and spatial prioritization. Each spatial benefit is presented with a case study.

### **2.1 SPATIAL ORIENTATION**

Because remotely sensed disturbance data is map-based, the position of historical disturbances may be considered precisely with respect to ownership boundaries and other features of interest. In 2004 the Washington Departments of Natural Resources and Fish and Wildlife commissioned a study of historical harvest activities that had affected habitat for the endangered Northern Spotted Owl (*Strix occidentalis caurina*). This information was sought to inform the State Forest Practices Board in their review of existing Forest Practice Rules. Anniversary-date biennial Landsat imagery was acquired covering the relevant area, and forest cover and basal area were modeled at each time step using training data from historical aerial photographs and a network of ground plots (described by Healey et al., 2006). Areas displaying significant abrupt drops in predicted cover were segregated into two classes: disturbances causing the loss of Spotted Owl habitat, and disturbances not causing such a loss. This segregation was possible because detected harvests had implicit pre- and post-activity estimates of cover and basal area, which could then be related to Forest Practice definitions of habitat conditions.

The resulting disturbance map was then summarized in two ways (see: Pierce et al., 2005). Habitat loss in areas with habitat conservation plans (HCP's – agreements between the federal government and a non-federal partner) was compared to rate of loss other areas: approximately 71% occurred on non-HCP lands. Habitat loss was also quantified specifically within Spotted Owl management circles; approximately a third of habitat harvested during the study period occurred within these circles. This analysis led to a recommendation on the part of the state of Washington to include better landscape-level planning to prevent forest loss both in and around owl habitat. State Forest Practice rules were subsequently changed to ensure more thorough consideration of habitat issues (Washington Forest Practices Board, 2007). While traditional sampling could theoretically produced the analyses that met this monitoring need, the number of samples needed to represent all of the relevant strata – owner, habitat type, proximity to management circles – would be unrealistically large, particularly given that disturbances covered a relatively small fraction of the landscape during the study period.

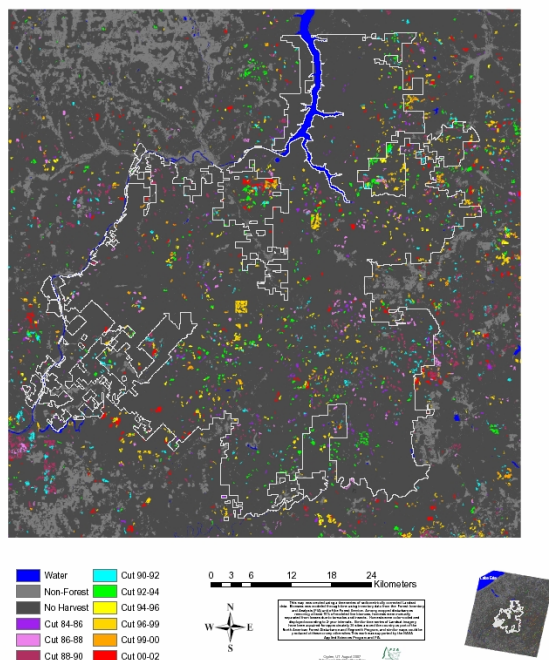
### **2.2 SPATIAL AND TEMPORAL CONTEXT**

Another type of information that a forest manager might require is perspective regarding how his/her presumably well-understood harvest patterns compare with historical harvest patterns or activities in neighboring forests. While a comprehensive and long-standing national forest inventory such as the Forest Inventory and Analysis (FIA) program in the United States can provide both temporal and spatial context regarding harvests (e.g. Smith et al., 2004), the scale of such national analyses rarely addresses local questions.

For example, managers at the Allegheny National Forest (ANF) in Pennsylvania (USA) keep a spatial record of all management activities. However, since they have no record of disturbances on other ownerships, they have no way to determine how the impact of their activities fits into the larger pattern of disturbance across the landscape. A collaborative effort between FIA, NASA and other federal and university research partners has addressed this need through remotes sensing. The goal of this collaboration, funded by the NASA's Earth Science Enterprise and Applied Sciences Program, is to increase the availability of remotely sensed disturbance information to the nation's forest management and policy communities. Under this program, biennial Landsat imagery going back to 1972 has been acquired for a number of sites

throughout the country. The ANF is in the center of one of these scenes. As was the case in Washington, inventory data was used to model a biophysical variable – in this case, biomass – over the entire scene at two-year intervals. There is evidence that such short intervals minimize the effects of re-growth and allow detection of less intensive disturbances (Sader et al., 2003). FIA field data, which is available on a randomized grid across the country, was used as training and validation data. A change detection algorithm was developed to make use of the temporal context available from long, dense time series. This algorithm (see Kennedy et al., 2007) fits generalized curves to the biomass “trajectory” modeled for each pixel, and allows detection of a number of types of forest change (including abrupt disturbance, re-growth, and gradual forest decline). Of mapped disturbances, harvests were identified (see Figure 1), allowing delivery of an analysis comparing current and historical harvest rates on the ANF with harvest rates of neighboring lands as well as with rates of disturbance caused by wind storms and insects.

**Harvests Removing at least 70% of Biomass Within and Outside the Allegheny National Forest, 1984-2002**



**Figure 1.** Map of harvests removing at least 70% of standing biomass both within and outside of the ANF from 1984 to 2002. Harvests from each 2-year interval are given an identifying color.

Modern forest managers understand how, where, and when their actions have affected forest structure. However, this understanding typically ends at the boundary of their property. The

consistency of remote monitoring over time and space can broaden the manager’s perspective and supply landscape-level context for one’s own management.

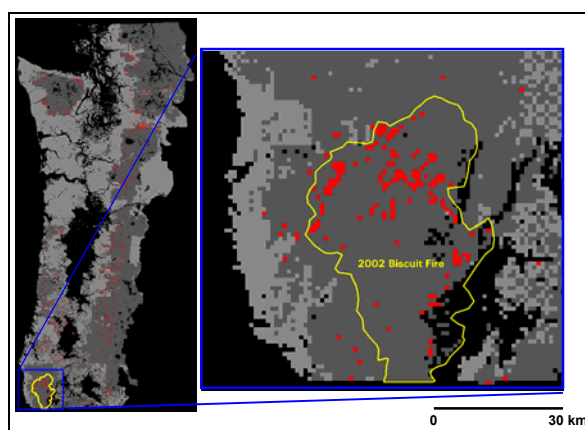
### 2.3 SPATIAL PRIORITIZATION

Managers of public forests are responsible for incorporating in their management decisions the values of the constituency they represent. In the United States, growing debate about the most appropriate direction of federal forest management has led to increased popular and legal scrutiny of federal forest management (Stankey, 2003). In this environment, managers need to demonstrate transparent and deliberate consideration of management options. Systematic monitoring is crucial in this process, and sample-based inventory, with its straightforward treatment of uncertainty, is an important tool in this regard. However, below the spatial level at which sample sizes are sufficient for estimation, traditional forest inventories have limited value for supporting systematic consideration of where management activities should take place. Remote sensing in some cases may fill this role because it provides wall-to-wall monitoring and can be applied consistently to all parts of the landscape.

The Northwest Forest Plan (NWFP, 1994) established a system of forest reserves on federal land in the Pacific Northwest (USA). A primary motivation for this plan was concern that losses of older forest habitat had put at risk the survival of species that used these habitats (e.g. the northern spotted owl, *Strix occidentalis*). While silvicultural treatments such as thinning may be used to accelerate the development of structural characteristics compatible with owl habitat (Tappeiner et al., 1997), funding for such treatments is limited (Spies, 2006). Prioritization of habitat recovery efforts is therefore critical, particularly in the context of declining owl populations. Spatially explicit records of forest loss developed with historical imagery may play a role planning such operations.

All of the stand-clearing disturbances from 1972 to 2002 within the NWFP area in the states of Washington and Oregon (approximately 14 million ha) were mapped using a time series of Landsat imagery (Cohen et al, 2002). These disturbances were combined with a map of the region’s older forests in 1972 (derived from historic Landsat imagery) to provide a 30-year record of where older forests have been lost (Healey et al., In Review). As a demonstration of the potential of remotely sensed disturbance information for supporting the spatial

prioritization of restoration activities, this information was queried with hypothetical but realistic criteria related to where limited restoration resources might be targeted. Specifically sought were 1x1 km cells that had lost the largest area of older forest and that met conditions of at least 25% ownership by the federal government and adjacency to large (>405 ha) blocks of mapped existing older forests. Figure 2 illustrates an area highlighted through this process; most identified areas had undergone either large fires or intensive harvest.



**Figure 1.** Map highlighting areas of high priority for restoration under hypothetical management criteria. Red pixels were in the top 5% by area of lost older forest among 1-km pixels that were at least 25% owned by the federal government and were also adjacent to existing blocks (>405 ha) of older forests. Dark grey represents federal forest, while light gray represents non-federal forest.

This approach could be tailored to the policies and scope of any forest manager, and creates a framework for systematic consideration of previous losses of older forests. Criteria could be varied by a private company to determine which among potential harvest units would minimize cumulative impacts upon habitat. The relatively fine spatial resolution but regional scope of the Landsat-derived disturbance map would permit these analyses at several scales. While stand-level inventory databases could theoretically be used for this purpose, keeping such databases current would not be cost-effective over large areas because of the required survey density. Areas highlighted through this process (displayed in red in Figure 2) would not automatically receive treatment; most proposed activities on public lands procedurally must be preceded by a stand exam in any case. However, using remotely sensed disturbance information provides a transparent way to systematically consider large areas, explicitly incorporate policy

directives into this consideration, and highlight local areas where management activities might be most appropriate.

### 3 CONCLUSIONS

Forest managers need accurate monitoring that is up to date and scientifically credible. This need extends to the monitoring of disturbances, which can significantly change the structure of large areas of forest in a comparatively short time. In many cases, sample-based estimation is a logical approach for monitoring disturbance and other trends in forest resources. However, for analyses where spatial relationships are critical or for applications where large areas must be considered systematically at the local level, remote sensing is an important complement to traditional forest survey.

### ACKNOWLEDGMENTS

The authors wish to thank the NASA Applied Sciences Program and the Interior West Forest Inventory and Analysis Program for their support of this synthesis.

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