

USE OF LANDSAT-BASED MONITORING OF FOREST CHANGE TO SAMPLE AND ASSESS THE ROLE OF DISTURBANCE AND REGROWTH IN THE CARBON CYCLE AT CONTINENTAL SCALES

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ABSTRACT

The exchange of carbon between forests and the atmosphere is a function of forest type, climate, and disturbance history, with previous studies illustrating that forests play a key role in the terrestrial carbon cycle. The North American Carbon Program (NACP) has supported the acquisition of biennial Landsat image time-series for sample locations throughout much of North America for the purpose of characterizing carbon fluxes associated with forest dynamics. Disturbance events such as harvests or fires can release large amounts of forest carbon, whereas subsequent sequestration of carbon by forest regrowth can be a much slower process. We are using national forest inventory reference data in conjunction with the NACP Landsat time-series to model and map forest disturbance and recovery dynamics and related biomass changes over time. With our approach, forest changes associated with disturbance and regrowth can be summarized at the scene level, and the results from multiple scenes can contribute to estimates of disturbance-related carbon flux at national scales. In our case, the NACP Landsat scenes were chosen using a probability-based sampling framework that allows systematic weighting of scene-level results in the production of national estimates of disturbance-related carbon flux. Specific parameters that we are mapping and estimating include: annual area disturbed, total standing biomass removed through disturbance, and biomass gained through regrowth following disturbance. These efforts rely upon techniques that we developed to take full advantage of the temporal context provided by the NACP Landsat time-series. In particular, we fit non-linear functions to the temporal trajectory of each pixel to minimize noise and to identify genuine losses and gains of forest cover and related biomass. Our analyses address disturbance patterns going back to at least 1984, and as far back as 1972. The historical context emerging from these analyses is improving our understanding of the roles of forest management and climate on national- to continental-scale carbon cycles.

Keywords: image-time-series, change-detection, biomass, curve-fitting, large-area, spectral-temporal-trajectory

1 INTRODUCTION

North America's forests are thought to be an important sink for atmospheric carbon. However, the size of the forest sink is highly uncertain because of a lack of detailed knowledge about forest disturbance, which limits the amount of carbon actually stored in biomass and soils. Understanding the role of forest disturbance in the continent's carbon cycle is one of the most critical problems currently being addressed by the North American geophysical science community.

For millennia, climate perturbations and natural forest disturbances associated with insects, disease, and fire have altered the carbon content of the continent's forests. Land-use change is not a new phenomenon either, as Native Americans often set fires to clear land for agriculture and wildlife. In more recent times forest change has accelerated, with land use and forest management over the past several centuries dramatically altering the area covered by forest, and the amount of carbon stored in forests by changing the continent's forest age structure.

Models of forest function and process have the capability to quantify forest carbon fluxes in relation to forest change over large spatial scales (e.g., Turner et al. 2007). Such models depend on a suite of measurements, including CO₂ and water flux and forest structure and growth. However, one critical knowledge gap that inhibits our ability to use these models to predict whether North American forests will be a long-term sink or source of atmospheric carbon is historic information at the continental scale on forest change that can be used to constrain and validate model predictions. National forest inventory programs in Canada, the United States, and Mexico are an important component of forest monitoring (e.g., Birdsey et al. 2006), but they lack the needed spatial and temporal detail for such a complex and dynamic problem as modeling

continental-scale forest carbon flux (Houghton, 2005). For this level of detail, over broad spatial and temporal scales, remote sensing of the land surface is required.

There are numerous satellite remote sensing systems currently providing data about forest change. However, only the Landsat system has a relatively long-term global record at a spatial resolution commensurate with management of individual forest stands. The Landsat program has been collecting data at the global scale for over 35 years with a spatial resolution of well under 100 m. Historic data from the Landsat system of satellites is playing a keystone role in linking forest inventories and process models to assess continental forest-related carbon flux. Much of the research needed to support this linkage is being done within the context of the North American Carbon Program (NACP) (Wofsy and Harriss 2002).

In this article, we describe two NACP-funded projects, one regional and one national, as examples of how Landsat data are being used to study the role of forest disturbance in the North American carbon cycle.

2 THE NORTH AMERICAN FOREST DYNAMICS (NAFD) STUDY

The NAFD study is designed to exploit the historic Landsat image archive and extant national forest inventory data to provide both statistical summaries and maps of forest change at the continental scale. Because over 1000 Landsat scenes are required to completely cover the continent's forest extent, an unequal-probability sampling design is being used (Kennedy et al. in preparation). The design relies on a forest type map to calculate the total forest area by forest type within each Landsat image area. Landsat samples are chosen randomly, but with constraints that balance several competing objectives: capture of

maximum forest area, capture of diverse forest types, inclusion of samples where significant prior research had occurred, and spatial dispersion of scenes. For the United States, 23 sample scenes have already been selected and processed, with an anticipated future expansion of sample size already accounted for in the probability-based design. We anticipate implementation of the design in Canada and Mexico over the next few years.

Each Landsat sample consists of a time-series of images, with an interval between image dates of one or two years starting in approximately 1972. The images are georeferenced to the earth and calibrated to surface reflectance using an advanced processing system developed for a complementary research project, known as LEDAPS (Masek et al. 2006). The Landsat time series is further processed with an algorithm that identifies image pixels containing forest that underwent significant change (Figure 1). The core of the algorithm is an index (*forestness*) that capitalizes on the expectation that interannual growing season reflectance of mature forest remains stable (Huang, in preparation). The logic of the algorithm is that deviations from expectation indicate forest change.

The primary purpose of the *forestness* algorithm is to identify pixel-level forest disturbance and assign a label containing year of disturbance (YOD) and magnitude of disturbance. The forest disturbance map is then assessed for errors in several ways, the most important of which is to use the national forest inventory data to link YOD to stand age. Anticipated improvements to the algorithm include characterization of rate of forest regrowth in previously disturbed stands.

An additional algorithm is being tested that converts reflectance to aboveground biomass (based on a statistical relationship between reflectance and inventoried biomass) and quantifies pixel-level biomass change for all forested pixels, including those that are only slowly changing. This algorithm,

trajectory-based change detection (TBCD), uses fitting parameters to quantify biomass pre- and post-disturbance, the rate of biomass loss for prolonged yet subtle disturbance, and the rate of biomass accrual.

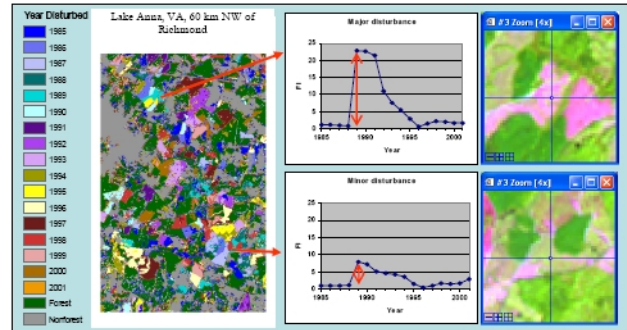


Figure 1. (left) Disturbance map produced using the forestness algorithm. (middle) Forestness temporal profiles of major (top) and minor (bottom) disturbances that occurred in 1989. The length of each double arrow indicates change magnitude. (right) Landsat image chips showing the occurrence of the two disturbances (Landsat Thematic Mapper bands 5,4,3 as RGB). The image chips show the appearance of non-vegetated reflectance after the major disturbance (top) and partially vegetated reflectance after the minor disturbance (bottom).

Adaptation of TBCD (Kennedy et al. 2007) to biomass time-series offers several new and powerful advantages over most existing forest change detection techniques. First, it leverages the time series of biomass predictions, fitting trends in the data to minimize the effect of changes in reflectance that are not associated with changes in biomass and thereby provide improved utility of Landsat data to estimate biomass for any point in time contained in the series (Figure 2). Second, the algorithm identifies different types of change, such as clearcut v. thinning harvest, insect attack followed by fire, and encroachment of forest into previously non-forested areas. Because all changes are in terms of biomass, errors in the produced maps can be directly assessed with inventory data. Moreover, as biomass is a directly relevant carbon quantity, the algorithm's products facilitate a host of new remote sensing applications to forest carbon modeling.

The two primary goals of the NAFD study are to derive statistical estimates of national- and continental-scale forest change, both to constrain process-based models of forest carbon flux and to map those changes to facilitate knowledge of spatially and temporally explicit factors that force changes in carbon dynamics at multiple scales. Disturbance metrics are still being validated for many of the sample scenes, but initial national-level estimates for the U.S. have been constructed from our preliminary *forestness* analyses. One result suggests that until 2000, the eastern US showed generally higher rates of forest disturbance than the western US.

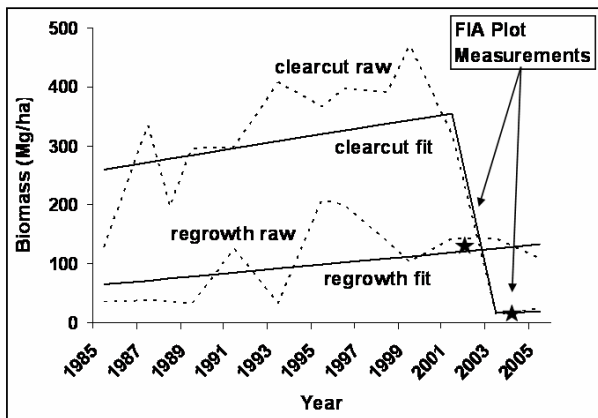


Figure 2. Sample biomass trajectories from central Oregon, demonstrating the effect of trajectory-based change detection (solid lines) on raw biomass predictions (dashed lines) for two recently disturbed FIA plots (plot-level biomass observations shown as stars).

The Landsat scene-area maps provide detailed spatial and temporal information at the local level. National- and continental-scale maps can be derived from these samples, in conjunction with other Landsat time-series not included in the original sample design using appropriate statistical procedures that are currently in development (Breidt and Opsomer 2007). Nationwide maps that we produce, and summary estimates derived from them will be validated, and then calibrated so as to provide consistency between estimates derived under the initial probability design and further

enhancements using additional scenes.

3 THE OREGON AND CALIFORNIA STUDY (ORCA)

The ORCA study is a prime example of how Landsat disturbance history maps can be used to link field-based observations and models to understand disturbance and climate effects on regional-level carbon balance. ORCA is testing and demonstrating an approach that uses field measurements to parameterize and validate a widely-used prognostic model of terrestrial carbon exchange (Biome-BGC), which is then applied to spatial data layers that include Landsat forest disturbance history (Turner et al. 2007).

A carbon budget has already been generated for the State of Oregon at a resolution of 30 m (Figure 3, from Turner et al. 2007). Landsat disturbance history provided the basis to account for all major fire and logging events over a 30-year period. Carbon emissions from fire were computed from area burned and biomass consumed. Modeled estimates for the flux contribution associated with harvest removals were checked against public harvest records. Comparison of simulation results with estimates of carbon stocks, and changes in carbon stocks, based on forest inventory data, showed good agreement.

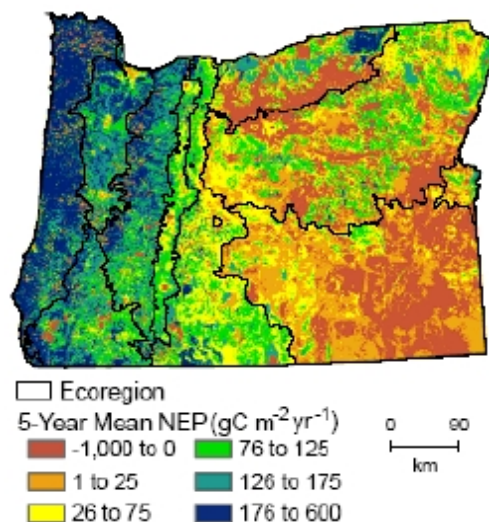


Figure 3. (top) Change detection map for Oregon with detail for a selected area. (bottom) The spatial distribution of net ecosystem production over Oregon (1996–2000). From Turner et al. 2007.

Currently, only coarse Landsat time-series (~ 5-year intervals) are used to map stand age of recently disturbed stands. There are several gas flux measurement towers within the ORCA study region where Biome-BGC is being thoroughly tested and improved. Using the denser time-series disturbance data now becoming available from the NAFD study for some tower locations, ORCA will provide a more detailed examination of the effects of forest thinning and less severely burned and variable regrowth after disturbance on model outputs.

4 FOREST DISTURBANCE AND THE NACP

Understanding how North America's forests are changing is a critical scientific, policy, and carbon management need. Consequently, within the NACP forest disturbance is a major research theme. Numerous projects within NACP are incorporating forest disturbance, to better understand the role of forests in the North American carbon cycle. We have shown how two specific projects within NACP are contributing to that understanding. For more information see the NACP website (<http://www.nacarbon.org/nacp/>).

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