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Forest Disturbance and North American Carbon Flux

PAGES 105–106

North America's forests are thought to be a significant sink for atmospheric carbon. Currently, the rate of sequestration by forests on the continent has been estimated at 0.23 petagrams of carbon per year, though the uncertainty about this estimate is nearly 50%. This offsets about 13% of the fossil fuel emissions from the continent [*Pacala et al.*, 2007]. However, the high level of uncertainty in this estimate and the scientific community's limited ability to predict the future direction of the forest carbon flux reflect a lack of detailed knowledge about the effects of forest disturbance and recovery across the continent.

The North American Carbon Program (NACP), an interagency initiative to better understand the distribution, origin, and fate of North American sources and sinks of carbon, has highlighted forest disturbance as a critical factor constraining carbon dynamics [*Wofsy and Harris*, 2002]. National forest inventory programs in Canada, the United States, and Mexico provide important information, but they lack the needed spatial and temporal detail to support annual estimation of carbon fluxes across the continent. To help with this, the NACP recommends that scientists use detailed remote sensing of the land surface to characterize disturbance.

Two investigations, the Landsat Ecosystem Disturbance and Adaptive Processing System (LEDAPS) study and the North American Forest Dynamics (NAFD) study, are providing scientists with new insight into understanding how forest disturbance in North America alters carbon sources and sinks. These and other efforts will supply information that can be used to better manage ecosystems and understand carbon budgets.

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Forests as Carbon Sources and Sinks

Forests take up carbon dioxide (CO_2) through photosynthesis. A large portion is released back to the atmosphere through respiratory processes, while some is stored as carbon in plant biomass. Carbon typically accumulates in woody biomass and soils for decades or centuries, until a disturbance event triggers accelerated release of stored carbon back to the atmosphere. A host of disturbance agents, such as fire, disease, insect outbreaks, drought, and harvesting, can perturb forest systems, each with different effects on carbon cycling.

Immediately after a major disturbance, a forest stand commonly acts as a source of carbon to the atmosphere until respiration from decomposers becomes less than photosynthetic uptake from regrowing

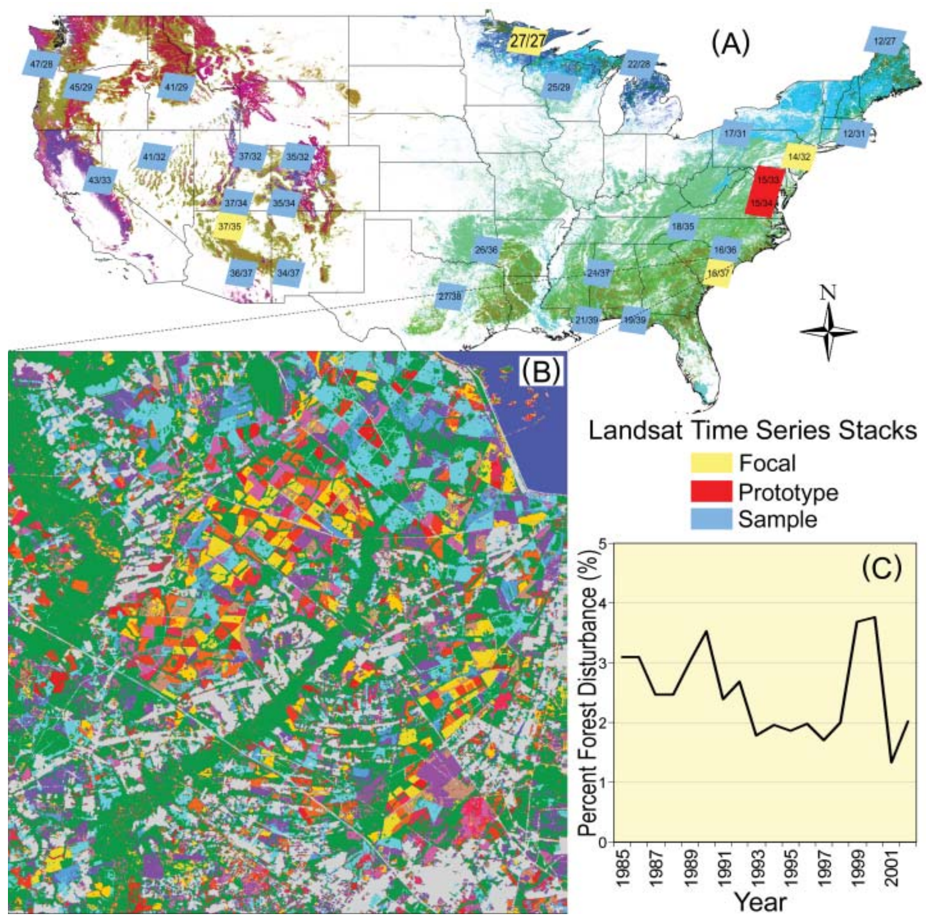

Fig. 1. (a) Location of samples selected across the conterminous United States, where biennial time series stacks of Landsat images (LTSS) were acquired and analyzed to map forest disturbance over the past three decades. The background forest group map shows that most of the forest groups in the United States have been represented by the samples. (b) An example disturbance map developed using the LTSS in a 28.5-kilometer-square area south of Lake Moultrie in South Carolina. Persisting forest, nonforest, and water are shown in green, gray, and blue, respectively. All other colors represent changes mapped in different years. (c) Percent of forest land disturbed annually, calculated according to the derived disturbance map for the entire South Carolina Landsat scene.

vegetation. The age at which a forest becomes a net carbon sink varies according to forest type, site productivity, and a host of other factors. Across landscapes, the net exchange of carbon is strongly controlled by the spatial distribution of stand ages, which in turn reflects the frequency of disturbance. In fact, one explanation for the forest sink in the eastern United States is that forests are regrowing on agricultural land abandoned in the nineteenth and twentieth centuries [*Houghton et al.*, 1999]. This implies the possibility of a smaller forest carbon sink in coming decades as these forests mature.

Several recent studies highlight the importance of forest disturbance for the terrestrial carbon cycle. For example, Hurricane Katrina disrupted lowland forests along the U.S. Gulf Coast in 2005. *Chambers et al.* [2007] estimated that 320 million large trees, corresponding to a biomass of 0.09–0.11 petagrams of carbon, were transferred from live to dead pools as a result of the storm. It will take several decades for this pool to respire completely to the atmosphere as vegetation recovers. *Wiedinmyer and Neff* [2007] examined the contribution of wildfire to the U.S. carbon budget and concluded that annual fire fluxes amounted to about 0.06 petagrams of carbon per year (±17%), equivalent to about 4% of U.S. fossil fuel emissions. In Canada the forest sector can be a source or sink of CO_2 to the atmosphere depending on the fire activities in a given year.

While individual disturbance events may result in carbon release to the atmosphere, generally these emissions will be matched over the long term by carbon uptake during recovery. The long-term net carbon flux from forests depends on changes in the rates of disturbance, such as changing rates of fire suppression, logging, or insect outbreaks.

Forest management and conversion also affect carbon cycling. The U.S. Forest Service has estimated that approximately 4.05 million hectares of forest lands are affected by harvest each year, corresponding to about 1.3% of the U.S. forest land base [*Smith and Darr*, 2004]. Timber harvest transfers aboveground biomass to wood products pools, which (if long lived) can be considered a type of carbon sink. *Pacala et al.* [2007] estimate that the United States and Canada sequester 0.06 and 0.01 petagrams of carbon per year, respectively, via the extraction of wood products.

Forest Disturbance Mapping: A Goal for the NACP

A number of research projects within the NACP are combining remote sensing and forest inventory data to map the extent and rate of forest disturbance. Given that disturbance processes vary in their extent, duration, and intensity, a multipronged approach makes sense, with different satellite technologies targeted toward different space and time scales. Coarse-resolution data such as those from the the U.S. National Oceanic and Atmospheric Administration's (NOAA) advanced very high resolution radiometer (AVHRR) and the NASA Moderate Resolution Imaging Spectroradiometer (MODIS) are being used to map transient phenomena occurring at the largest scales, including herbivorous insect outbreaks, drought stress, and storm damage [*Potter et al.*, 2005; *Chambers et al.,* 2007]. These data are also being used for estimating emissions from fires and for global mapping of active fires and burned area.

The Landsat satellite program (managed jointly by NASA and the U.S. Geological Survey) has been collecting global land data for more than 35 years with spatial resolutions of less than 100 meters, a scale commensurate with that needed by those who manage individual forest stands. Historic Landsat data play a key role in linking forest inventories and process models to assess continental forest-related carbon fluxes. The LEDAPS project is using a decadal collection of Landsat imagery to map stand-replacing forest disturbance "wall to wall" across North America, initially for the decade between 1990 and 2000 [*Masek et al.*, 2006]. While the 10-year revisit interval cannot capture all stand-replacing disturbance events in the decade (due to rapid forest regeneration), and misses partial or moderate disturbances, the LEDAPS maps do portray the geographic distribution of disturbance intensity across the continent.

The NAFD Study

In contrast to the LEDAPS approach, the NAFD study more fully exploits the temporal Landsat image archive and national forest inventory data to provide both statistical summaries and maps of forest change at the continental scale. Dense time series of Landsat imagery are being prepared for a sample of Landsat frames across the continent. The sampling approach limits data processing needs by avoiding a wall-to-wall analysis at every location. Landsat sample locations 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 (R. E. Kennedy et al., manuscript in preparation, 2008). For the United States, 23 sample scene locations have already been selected and processed (Figure 1), and additional images will be selected for Canada and Mexico.

Each Landsat sample consists of an image time series for 1972–2005, with an image interval of 1–2 years. Forest disturbance information is extracted using two approaches. The first is a spectral index that identifies forest disturbance and regrowth on the assumption that mature forest reflectance remains stable over time. A complementary algorithm is being tested that converts reflectance to aboveground live biomass based on a statistical relationship between Landsat reflectance and biomass from colocated forest inventory plots. The algorithm then extends this relationship through the images' time series. With these data, the algorithm then uses a new approach, called trajectory-based change detection (TBCD), to quantify biomass before and after the disturbance, the rate of biomass loss for prolonged yet subtle disturbance, and the rate of biomass accrual [*Kennedy et al.*, 2007].

The NAFD study is deriving statistical estimates of national- and continental-scale forest change, including phenomena such as partial harvest, thinning, and insect damage, which may not always destroy the whole stand. Although disturbance metrics are still being validated, initial estimates for the United States suggest that eastern states showed higher rates of forest disturbance than western states due primarily to high rates of harvest in the southeast. Disturbance rates of 1–1.5% of forest cover per year were common during the 1980s and 1990s across the United States as a whole.

While the initial phase of NAFD focused on U.S. forests, the project now is expanding to include samples from Canada and Mexico. As a signatory nation of the Kyoto Protocol, Canada has focused on meeting the required reporting activities, which to date have centered on the managed southern forests. The northern unmanaged forest land of Canada is not as well characterized, and the placement of Landsat samples in this region will provide new insights on carbon fluxes. Currently, much less is known about the disturbance history of Mexico, but Mexico's national forest inventory, like that of Canada and the United States, is cooperating closely with the NAFD effort.

Integration of Disturbance Products Into Carbon Models

As new data products on forest disturbance emerge, they are being integrated into biogeochemical models to generate more robust estimates of ecosystem carbon fluxes. *Masek and Collatz* [2006] presented a prototype of one approach using a NAFD disturbance record from central Virginia. This approach used a biogeochemical model to predict carbon pools and fluxes (including net carbon flux) to the atmosphere given forest age maps derived from the Landsat analyses.

A study in Oregon and California ("ORCA") is testing and demonstrating an approach that uses field measurements to parameterize and validate a widely used prognostic model of terrestrial carbon exchange, called Biome-BGC. Initial results show good agreement [*Turner et al.,* 2007; *Law et al.,* 2006].

The recent Landsat-based disturbance history from the NAFD project is also being used to help interpret longer-term land cover change reconstructions spanning the past 300 years that underpin bookkeeping models of carbon sources and sinks [*Houghton et al.,* 1999]. Bookkeeping analyses show a forest carbon sink that is only 10–30% of the sink estimated from United States's forest inventories. The current NACP study will compare analyses produced under NAFD with these bookkeeping analyses for the coincident time period (1972–2005) to reveal strengths and weakness of those two approaches, and harmonize estimates of carbon flux.

Future Directions

Understanding how North America's forests are changing is a critical scientific, policy, and carbon management need. Consequently, forest disturbance is a major research theme within the NACP. As the NACP moves toward continental syntheses of carbon dynamics, the availability of data on forest disturbance will help reduce uncertainties regarding current and future fluxes of carbon to the atmosphere.

Nonetheless, certain challenges remain. First, with several groups tackling the problem of disturbance mapping independently, there is a need for improved integration. At the January 2007 NACP investigators meeting, a synthesis activity was endorsed that centered on producing a "consensus" record of ecosystem disturbance and land cover change. Such an effort would also help mitigate one of the main weaknesses of the satellite-based approaches discussed in this article: the short time period (<40 years) covered by the remote sensing record. By matching satellite-based land cover dynamics from the past three decades with longer-term dynamics derived from inventory data, ecological reconstructions, and social science data, a more consistent record of land dynamics can be assembled.

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