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Regional rates of young US forest growth estimated from annual Landsat disturbance history and IKONOS stereo imagery

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ABSTRACT

Forests of the Contiguous United States (CONUS) have been found to be a large contributor to the global atmospheric carbon sink. The magnitude and nature of this sink is still uncertain and recent studies have sought to define the dynamics that control its strength and longevity. The Landsat series of satellites has been a vital resource to understand the long-term changes in land cover that can impact ecosystem function and terrestrial carbon stock. We combine annual Landsat forest disturbance history from 1985 to 2011 with single date IKONOS stereo imagery to estimate the change in young forest canopy height and above ground live dry biomass accumulation for selected sites in the CONUS. Our approach follows an approximately linear growth rate following clearing over short intervals and does not estimate the distinct non-linear growth rate over longer intervals. We produced canopy height models by differencing digital surface models estimated from IKONOS stereo pairs with national elevation data (NED). Correlations between height and biomass were established independently using airborne LiDAR, and then applied to the IKONOS-estimated canopy height models. Graphing current biomass against time since disturbance provided biomass accumulation rates. For 20 study sites distributed across five regions of the CONUS, 19 showed statistically significant recovery trends ($p < 0.001$) with canopy growth from 0.26 m yr^{-1} to 0.73 m yr^{-1}. Aboveground live dry biomass (AGB) density accumulation ranged from 1.31 t/ha yr^{-1} to 12.47 t/ha yr^{-1}. Mean forest AGB accumulation was 6.31 t/ha yr^{-1} among all sites with significant growth trends. We evaluated the accuracy of our estimates by comparing to field estimated site index curves of growth, airborne LiDAR data, and independent model predictions of C accumulation. Growth estimates found with this approach are consistent with site index curves and total biomass estimates fall within the range of field estimates. This is a viable approach to estimate forest biomass accumulation in regions with clear-cut harvest disturbances.

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1. Introduction

Eastern forests of the US were found to be a large contributor to the global atmospheric carbon (C) emissions sink through regeneration from past disturbance (Canadell et al., 2007; Caspersen et al., 2000; Pacala et al., 2001). The nature and magnitude of this sink is still uncertain and recent studies have sought to define the dynamics that control its strength and longevity (Dangal, Felzer, & Hurteau, 2014; Pan et al., 2011a; Powell, Cohen, Kennedy, Healey, & Huang, 2014). Forest disturbance history is directly related to this sink (Pan et al., 2011b), and remote sensing is one of the best tools to estimate and understand regional changes in forest cover (Hansen et al., 2013).

Remote sensing-based forest structure estimates from airborne and spaceborne light detection and ranging (LiDAR), radio detection and ranging (RADAR), and very-high spatial resolution (VHSR) stereo image data are all capable of providing vegetation structural information that may be used to predict the distribution of aboveground biomass (Gao, 2007). Combining a time-series of forest disturbance history with single-date forest structure information could yield basic regional information on rates of forest recovery. By combining remote sensing data on forest structure with modeling, one could potentially predict the strength and longevity of the land use forest C sink.

Satellite remote sensing with the time series of Landsat sensors is a vital resource to monitor long-term changes in forest cover (Goward et al., 2008; Hansen et al., 2013; Masek et al., 2013; Sexton et al., 2013). To estimate annual rates of forest disturbance, the North American Forest Dynamics (NAFD) project assembled annual Landsat time-series in 50 path-rows distributed throughout the Contiguous United States (CONUS). More recently, over 23,000 images were used to create a wall-to-wall forest disturbance map for the CONUS (Masek et al., 2013; Goward et al., in prep). The vegetation change tracker (VCT) algorithm developed by Huang et al., 2010 and used in these projects has shown to be a reliable resource to acquire annual forest

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disturbance history (Huang, Ling and Zhu, 2015; Huang, Schleeweis, Thomas and Goward, 2011). The VCT forest disturbance product estimates annual time of stand clearing disturbance (clear-cut harvest with 0–10% tree cover remaining) (Thomas et al., 2011), but by itself does not estimate quantitative information about carbon loss or gains through forest harvesting, regrowth or regeneration. In this study, we define regrowth or regeneration as an increase in canopy height—i.e. forest canopy growth post VCT estimated forest disturbance. This information is important to map the locations of strong terrestrial C sinks, furthermore, ecosystem responses following disturbance can be included in carbon models (Williams, Collatz, Masek, & Goward, 2012).

Traditionally, the most accurate forest structural estimates have been based on airborne LiDAR sensors that actively send pulses of laser light through the canopy and measure the time-of-flight to deduce ranging and permit estimates of vegetation height from predictions of echo heights (Gao, 2007; Lim, Treitz, Wulder, St-Onge, & Flood, 2003). Unfortunately, only one space-borne sensor, the Geosciences Laser Altimeter System (GLAS) onboard the Ice Cloud and Elevation Satellite (ICESat) has collected LiDAR data that can be used to estimate forest structure globally (Harding & Carabajal, 2005). Since these data are acquired170 m apart along-track and from 100s of meters to ~30 km apart across-track, and because this sensor is no longer operational, these data have limited utility in understanding site level forest structure dynamics. A previous study by Dolan, Masek, Huang, and Sun (2009) successfully combined GLAS and VCT estimates to calculate rates of forest growth in three regions of the eastern US. This study found growth rates of 0.6 m yr^{-1} to 1.2 m yr^{-1}, but it had a small sample size because of the limited extent of VCT products at the time, and a limited number of acceptable waveforms within each Landsat path/row. Similar work was performed in the Brazilian Amazon by Helmer, Lefsky, & Roberts, 2009 estimating rates of biomass accumulation in secondary and old-growth forests by combing time-series Landsat and GLAS. Numerous airborne LiDAR sensors have been developed and flown for forest studies (Blair, Rabine, & Hofton, 1999; Cook et al., 2013; Means et al., 1999; Naesset, 1997; Nelson, Parker, & Hom, 2003), but they typically only estimate a synoptic snapshot, i.e., one observational date or period. Other studies have evaluated repeat over flights to estimate growth (Hopkinson, Chasmer, & Hall, 2008; Hudak et al., 2012; Naesset & Gobakken, 2005), but airborne LiDAR data collection can be costly to conduct large-area surveys.

Stereoscopic aerial photography was the primary tool used to gather forest structural information prior to the advent of operational airborne LiDARs. VHSR satellite data provide large areas of coverage, typically larger than ~10 × 10 km and most commercial VHSR sensors collect stereoscopic imagery. All DigitalGlobe satellites (IKONOS-2, Quickbird-2, Geoeye-1, WorldView-1, WorldView-2, and WorldView-3) can collect within-track stereo imagery and the volume and coverage of these data has grown exponentially with the WorldView series of satellites (Neigh, Masek, & Nickeson, 2013). From the launch of IKONOS in 1999, over a decade of stereoscopic measurements from multiple commercial sensors exist. These commercial data from DigitalGlobe are currently accessible at no direct cost to researchers who are funded by US government agencies and those who support US government interests (Neigh et al., 2013). This enables the application of large volumes of stereo VHSR data to be used in forestry studies that might otherwise be cost prohibitive.

Here we use the Landsat annual VCT record and overlapping stereo IKONOS images to estimate structural changes of forests following stand clearing disturbance. VHSR stereo optical digital surface models (DSMs) combined with high-resolution digital terrain models (DTMs) have shown to be an effective tool to estimate forest canopy heights (Hobi & Ginzler, 2012; Neigh et al., 2014; St-Onge, Hu, & Vega, 2008; Vega & St-Onge, 2008). We seek to understand rates of forest growth in multiple ecoregions of the US by combining disturbance history from Landsat with canopy height models (CHMs) from IKONOS. Here, we evaluate and quantify the viability of this approach on a regional basis from New England, South Atlantic, Eastern South Atlantic, Western South Atlantic and Pacific Northwest. This method could provide important empirical evidence on stand age and volume that C-cycle models could use to help predict the strength and longevity of the US forest C sink.

2. Study areas

Our study areas comprise twenty IKONOS stereo pairs distributed predominately in the eastern US and the Pacific Northwest (Fig. 1). Our goal was to have stereoscopic forest structure estimates in a diverse set of ecological regions of the US to understand rates of growth in multiple forest types. Archived stereo IKONOS data dictated the exact locations of our study sites. These data primarily have been collected over urban areas, but many suburban and rural stereoscopic images are available. Our sample sites are typically the same dimensions of a standard IKONOS image measuring ~10 × 10 km, with the exact dimensions dependent upon the viewing geometry of the image acquisitions. We focused on Landsat path-rows that exhibited large amounts of forest disturbance (>3% yr^{-1}) over time as recorded by the NAFD VCT products to insure that a large number of samples (>100,000 1 × 1 m pixels) were available to estimate forest regeneration.

3. Data and methods

The overall analysis approach involved the following steps:

1. Within a given Landsat multi-temporal data stack, estimate forested areas that were cleared and then regenerated to forest. Use the VCT data with a magnitude threshold from 1985 to 2011, to estimate stand age for stand clearing disturbances.
2. In these regenerating stands, use single-date IKONOS stereo imagery to estimate heights of stands of various ages, a *space-for-time* swap, in order to predict composite growth vs. age (yield) curves from the time of IKONOS acquisition.
3. Use spatially coincident airborne laser scanning (ALS) data and IKONOS stereo data to identify those IKONOS height metrics most closely related to first-return LiDAR height metrics.
4. Use temporally and spatially coincident ALS and FIA estimates to develop simple regressions to predict ground estimates of above ground biomass (AGB) density in tons per hectare (t/ha) as a function of first-return ALS height estimates.
5. Substitute IKONOS height estimates (steps 2 & 3) in the FIA–ALS regressions (step 4) to predict AGB for stands of various ages, where age is estimated using the Landsat time series (step 1).
6. Estimate AGB accumulation rates for local areas based on these multi-year AGB estimates (step 5).

We describe the data sets used in this analysis below.

3.1. Landsat VCT

Landsat time series stacks have been processed using VCT from 1984 to 2011 for the entire CONUS to map annual forest disturbance (Goward et al., 2008; Huang et al., 2010; Masek et al., 2013). To remove cloud cover in these annual 30 m products, often multiple images within a year were composited to remove cloud contamination and estimate the timing (year) and spectral magnitude of disturbance events. More information about the algorithm is available in Huang et al., 2010. We used VCT data to: 1) estimate time since forest stand clearing disturbance and apply it to IKONOS CHMs with a *space-for-time* approach; and 2) exclude forest disturbances that occurred after the IKONOS acquisition as a height bias could result from acquisition differences producing a false comparison of values between dates of data collection. We also note that forest degradation affecting individual crowns such as thinning or partial harvest are not estimated in VCT products at the same accuracy as clear-cut disturbance. VCT estimates date of stand clearance, with no definitive time of regeneration start, making this