Remote Sensing of Environment 151 (2014) 44–56

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

# Estimation of forest aboveground biomass in California using canopy height and leaf area index estimated from satellite data

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ARTICLE INFO

*Article history:*
Received 19 November 2013
Received in revised form 3 January 2014
Accepted 12 January 2014
Available online 11 March 2014

*Keywords:*
Aboveground biomass
Leaf area index
Canopy height
Landsat
Uncertainty assessment

ABSTRACT

Accurate characterization of variability and trends in forest biomass at local to national scales is required for accounting of global carbon sources and sinks and monitoring their dynamics. Here we present a new remote sensing based approach for estimating live forest aboveground biomass (AGB) based on a simple parametric model that combines high-resolution estimates of leaf area index (LAI) from the Landsat Thematic Mapper sensor and canopy maximum height from the Geoscience Laser Altimeter System (GLAS) sensor onboard ICESat, the Ice, Cloud, and land Elevation Satellite. We tested our approach with a preliminary uncertainty assessment over the forested areas of California spanning a broad range of climatic and land-use conditions and find our AGB estimates to be comparable to estimates of AGB from inventory records and other available satellite-estimated AGB maps at aggregated scales. Our study offers a high-resolution approach to map forest aboveground biomass at regional-to-continental scales and assess sources of uncertainties in the estimates.


## 1. Introduction

Estimating and preserving the carbon stock in forests can help devise sequestration strategies and reduce emissions from deforestation and degradation (REDD) (Canadell et al., 2007; IPCC, 2007; Miles & Kapos, 2008; UNFCC) as well as promote carbon credits to offset greenhouse gas emissions from other sources. Forest carbon stocks that change dynamically over time can be detected through periodic mapping of the total forest biomass (Baccini et al., 2012; Gurney & Raymond, 2008; Saatchi, Harris, et al., 2011; Saatchi, Marlier, Chazdon, Clark, & Russell, 2011). National inventories (e.g. the U.S. Forest Service Inventory and Analysis Program; FIA) provide the most detailed field estimates of forest biomass and disturbance history at national scale (Keith, Mackey, Berry, Lindenmayer & Gibbons, 2010). Although, methods for harmonizing forest inventory data are present at a national scale (McRoberts et al., 2009), the utility of such inventories for global-scale studies is limited because of national differences in measurement strategies, sparse sampling and out of date observations (Houghton, 2005). In addition, most inventories are designed to provide inferences only for administrative units or large regions. This is an important limitation because reducing the uncertainty in emissions estimates requires spatially continuous measurements of forest carbon that are fine enough to capture the variability over a landscape that may undergo natural disturbances, succession or land-use changes.

Remote sensing allows mapping the aboveground portion of total forest biomass (AGB) over wide geographical extents, overcoming problems of field data underrepresentation (Gibbs, Brown, Niles & Foley, 2007; Lu, 2006; Saatchi, Houghton, Dos Santos Alvalá, Soares & Yu, 2007). Canopy reflectance measured by passive optical sensors and radar backscatter has been shown to correlate with field estimates of AGB densities (AGB value by instrument's footprint) (Foody, Boyd & Cutler, 2003; Steininger, 2000) but only up to densities of 300–400 Mg/Ha, after which the reflective measures show an asymptotic behavior with canopy closure (Saatchi et al., 2007). Space-borne LiDAR has improved the accuracy of the estimates of canopy vertical structure (Asner et al., 2010; Drake, Dubayah, Knox, Clark & Blair, 2002; Lefsky, Harding, Cohen, Parker & Shugart, 1999), but its sparse availability requires the fusion of multiple sources of data for large area mapping of AGB. Global forest height data estimated by the Geoscience Laser Altimeter System (GLAS; Harding & Carabajal, 2005), onboard the Ice, Cloud, and land Elevation Satellite (ICESat), have been combined with other remote sensing data (e.g. MODIS and ALOS PALSAR) and ground data aided with predictive models, to map the biomass density of forests across

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http://dx.doi.org/10.1016/j.rse.2014.01.025
0034-4257/

large regions of the globe (Baccini, Laporte, Goetz, Sun & Dong, 2008; Boudreau et al., 2008; Goetz et al., 2009; Saatchi, Harris, et al., 2011; Saatchi, Marlier, et al., 2011). One limitation of this approach is that field data-driven model estimates of AGB have large uncertainties in regions where inventory data is absent and the inferences on under-sampled areas are usually based upon limited training data. Few studies have analyzed the theoretical linkages between remotely sensed vegetation indexes and biomass (Shi et al., 2013; Zhang & Kondragunta, 2006), which could advance the investigation of predictors and approaches for AGB estimation. In addition to coarse resolution mapping of biomass, there are increasing demands and attempts for estimating AGB density at finer resolution from Landsat reflectances (NASA's National Carbon Monitoring System Program; Avitabile, Baccini, Friedl & Schmullius, 2011; Lu et al., 2012) and other commercial satellites over continental-to-regional scales.

Uncertainty assessment is an essential component of AGB estimation based on remote sensing data because of the diversity in data sets involved, from satellite data to field-based samples and allometric models (Wulder et al., 2012). Because of differences in spatial resolution associated with field inventory plots, remotely sensed data, and the final AGB map, the sampling errors are difficult to assess through an error propagation approach (Mitchard et al., 2011). Many prediction models rely upon local data tuning, which causes the uncertainty of the experiment to vary depending on the data. To understand the contribution of each source of uncertainty in the AGB estimation, a general error propagation model is necessarily applied to a simple biomass estimation approach at uniform scale.

The objective of the study is to estimate AGB using a methodology based on the following premises:

(a) We are able to integrate Landsat-estimated leaf area index (LAI) as a measurable structural attribute of canopy with forest height from GLAS to estimate a continuous height map using a simple parametric model at a spatial resolution of 30 m × 30 m;
(b) We can estimate the AGB density from the continuous height map from (a) using a height-to-biomass functional relationship based on inventory data; and
(c) We are able to estimate uncertainties for our AGB density due to errors in input data sources and model parameters using a Monte Carlo based error propagation model.

In the following sections we describe the region of study, data and methods used to estimate the AGB density, characterizing uncertainty in the final AGB product, and approaches to compare AGB density estimates with inventory based plot data and existing satellite-based AGB estimates. We estimate AGB using the computational facilities available at National Aeronautics and Space Administration (NASA) Earth Exchange (NEX) and thus refer to the biomass product as NEX-AGB. Our estimates of AGB density are comparable to Forest Inventory and Analysis (FIA) based AGB assessments and other satellite based estimates of AGB density at different aggregated scales (e.g. for counties and subecoregions).

## 2. Data

### 2.1. Data for model construction

#### 2.1.1. Land cover, elevation, and sub-ecoregion map

The study area for prototyping our methodology is the state of California, USA, which encompasses various eco-climatic zones with large variations in AGB. The National Land Cover Database (NLCD) 2006 provides accurate and consistent land cover information at a spatial resolution of 30 m × 30 m for the Conterminous United States (CONUS) and is an updated version of NLCD 2001 (WWW1). We used the NLCD 2006 map to select forested areas over California — the total forested land is approximately 9.54 million hectares, with evergreen forests comprising the majority in the Sierra Nevada and the Pacific Northwest. The producer's accuracy for forest classes of NLCD 2006 was 94% for the continental United States (Wickham et al., 2013). In addition, we used a map of the ecological subregions of California with terminologies consistent with the FIA records and available at 1:500,000 to 1:1,000,000 scale from the US Forest Service (USFS) ECOMAP Team (WWW2). A total of 147 sub-ecoregions were used in our analysis. The National Elevation Dataset (NED) was used to verify the GLAS elevation estimates and generate slopes for height correction. Gesch (2007) reports that the root-mean-square error (RMSE) of NED is 2.44 m nationwide.

#### 2.1.2. Landsat data

We used the USGS Global Land Survey (GLS) 2005 Landsat data for California (total of 45 cloud-free Landsat scenes). The GLS imagery consisted of both Landsat 5 and gap-filled Landsat 7 data at a spatial resolution of 30 m × 30 m with core acquisition dates from 2005 to 2006 (Gutman, Byrnes, Masek; Covington, Justice, Franks, & Headley, 2008; Gutman, Huang, Chander, Noojipady & Masek, 2013; WWW3). Each Landsat scene consists of a single day, mostly cloud-free acquisition, and the time of acquisition generally falls during leaf-on, peak of growing conditions for the location. Data recorded in 2004 and 2007 were used to replace GLS scenes with low image quality or excessive cloud cover. Over California, selecting images based on the peak of the growing season within the footprint of the Landsat scene results in spatial discontinuities once the scenes are mosaicked together (e.g. the growing season for crops near the San Francisco Bay Area peaks around April while the vegetation in adjacent scenes covering portions of the Sierra Nevada peaks later in the summer, in July or August). To rectify this issue, we harmonized the specific scenes to the same acquisition time (July–August) by replacing the April scenes with other cloud-free Landsat 5 scenes for July or August of the same year. If no Landsat 5 scenes were available during the GLS acquisition time, we chose scenes of the previous year or the year after. The harmonized mosaic of Landsat imageries has been previously used to map California LAI producing results comparable to the standard MODIS LAI product with error of 0.5 (Ganguly et al., 2012); however the remaining inconsistencies in acquisition dates of Landsat imageries contribute to uncertainty in the final AGB estimate.

#### 2.1.3. GLAS canopy height

The Geoscience Laser Altimeter System (GLAS) staged in the Ice, Cloud, and land Elevation Satellite (ICESat) emits a 1064 nm laser pulse at an elliptical ground footprint of ~64 m diameter (Abshire et al., 2005), and the echo waveform of the laser pulse is recorded at the sensor system. The echo waveform data is referenced as the GLAS/ICESat L1A Global Altimetry Data (or GLA01). Associated with the GLA01 product is the GLAS/ICEsat L2 Global Land Surface Altimetry Data (GLA14) product. GLA14 provides the geo-location of each footprint along with other parameters estimated from the waveform, such as the signal beginning and the echo energy peaks. In this study all the available GLA01 and GLA14 data with release version 3.1 for the time period from 2003 to 2007 were used to estimate the canopy height. Data after November 2007 were not used because of a decline in the laser power of the GLAS instrument (Lefsky, 2010).

#### 2.1.4. Forest inventory data

The FIA Program of the USDA Forest Service measures and records information about forests at well designed ground plots (a standard FIA base plot includes roughly 1 sample location per 2400 ha). In this study, we gathered estimates of AGB, height, and the number of trees per area from the FIA database (FIADB - Version 4.0) for each plot within California (WWW4) for the time period from 2001 till 2007. A total of 2205 plots is available for California.