Available online at www.sciencedirect.com
ScienceDirect
Remote Sensing of Environment 109 (2007) 482–499
Remote Sensing of Environment
www.elsevier.com/locate/rse

An empirical InSAR-optical fusion approach to mapping vegetation canopy height

Wayne S. Walker [a,*], Josef M. Kellndorfer [a], Elizabeth LaPoint [b], Michael Hoppus [b], James Westfall [b]

[a] *The Wood Hole Research Center, Falmouth, MA, United States*
[b] *USDA Forest Service, Forest Inventory and Analysis Program, United States*

Received 21 November 2006; received in revised form 1 February 2007; accepted 3 February 2007

Abstract

Exploiting synergies afforded by a host of recently available national-scale data sets derived from interferometric synthetic aperture radar (InSAR) and passive optical remote sensing, this paper describes the development of a novel empirical approach for the provision of regional- to continental-scale estimates of vegetation canopy height. Supported by data from the 2000 Shuttle Radar Topography Mission (SRTM), the National Elevation Dataset (NED), the LANDFIRE project, and the National Land Cover Database (NLCD) 2001, this paper describes a data fusion and modeling strategy for developing the first-ever high-resolution map of canopy height for the conterminous U.S. The approach was tested as part of a prototype study spanning some 62,000 km^2 in central Utah (NLCD mapping zone 16). A mapping strategy based on object-oriented image analysis and tree-based regression techniques is employed. Empirical model development is driven by a database of height metrics obtained from an extensive field plot network administered by the USDA Forest Service–Forest Inventory and Analysis (FIA) program. Based on data from 508 FIA field plots, an average absolute height error of 2.1 m (r=0.88) was achieved for the prototype mapping zone.

Keywords: Vegetation canopy height; Scattering phase center height; InSAR; Radar; Interferometry; Optical; Multi-spectral; SRTM; Landsat ETM+; Forest inventory; FIA; DEM; Object-oriented; Segmentation; Regression trees

1. Introduction

1.1. Motivation

Spatially extensive and accurate maps of vegetation canopy height are of value not only to ecologists and land managers working in diverse fields such as biodiversity conservation, wildfire risk assessment, and timber production, but also to climate change scientists focused on reducing the uncertainty associated with the carbon cycle component of Earth's climate system. High-resolution maps of canopy height have the potential to significantly improve the accuracy of aboveground biomass and carbon stock baselines upon which models of future climate change necessarily depend. Reliable baseline information is also needed for measuring and monitoring carbon fluxes and for verifying emissions reductions in the context of national and international carbon accounting strategies.

Although the forests of the United States and other mid- to high-latitude nations are covered by extensive inventory plot networks, these data are largely inadequate for the provision of high-resolution estimates of aboveground biomass and carbon stocks. Whereas dry biomass, which contains 45 to 50% carbon by weight (Linder & Axelsson, 1982; Reichle et al., 1973), may be well quantified for the localized areas where measurements exist, extrapolation across larger unsampled regions can contribute to considerable estimate uncertainty (Houghton & Goodale, 2004). Consequently, at regional to continental scales, estimates of multi-dimensional forest structural metrics are necessarily acquired through the use of remote sensing technologies in concert with ground-based measurements derived from national forest inventories. The practice of leveraging the combined strengths of forest inventory and

* Corresponding author. Tel.: +1 508 540 9900.
E-mail address: wwalker@whrc.org (W.S. Walker).

0034-4257/$ - see front matter
doi:10.1016/j.rse.2007.02.001

satellite image data dates back to the early 1990s in Finland (Tomppo, 1991). More recent examples include applications in northern Europe and the United States (Huang et al., 2002; McRoberts & Liknes, 2005; Reese et al., 2002, 2003; Tomppo et al., 2002).

Numerous approaches have been put forth for the provision of aboveground biomass estimates using the range of available remote sensing technologies including passive optical (e.g., Dong et al., 2003; Myneni et al., 2001), radar (e.g., Dobson et al., 1992; Ranson et al., 1997), and lidar (e.g., Drake et al., 2002; Hyde et al., 2005; Lefsky et al., 1999a,b); however, a technique has yet to be presented that is consistent, reproducible, and applicable across broad geographic extents (Rosenqvist et al., 2003). This is largely due to the fact that biomass is a three-dimensional metric — the accurate estimation of which requires biophysical measures, and therefore remote sensors, that capture both the horizontal (e.g., canopy density/cover) and vertical (e.g., canopy height) structural character of the vegetation (Mette & Hajnsek, 2003; Mette et al., 2004; Treuhaft et al., 2004). While the science of acquiring remotely sensed estimates of horizontal vegetation structure has matured considerably over the past 25 years, only in the last decade have significant advances in instrument development made it possible to obtain consistent and accurate measurements of canopy height and related metrics of vertical vegetation structure (e.g., Lefsky et al., 2002; Treuhaft & Siqueira, 2000). Motivated by these advancements, this research focuses on the three-dimensional structure of forest vegetation in an effort to expand the scientific basis for regional- to continental-scale carbon accounting. Specifically, this research presents an approach to the generation of high-resolution, spatially extensive maps of vegetation canopy height. The approach is the foundation for an ongoing NASA-sponsored project with the ultimate goal of generating the first-ever circa-2000 baseline dataset of vegetation canopy height, aboveground biomass, and carbon stocks for the conterminous U.S. This project is possible, in part, because of the complimentary nature and quasi-synchronous development of several national digital geospatial datasets. The following section provides a brief introduction to these datasets.

1.2. Confluence of national mapping efforts

The last several years have been marked by an unprecedented confluence of high-resolution geospatial data sources and derived products for the conterminous U.S. The first of these datasets was acquired early in 2000 when the NASA-JPL Shuttle Radar Topography Mission (SRTM) used C-band (5.6 cm, 5.3 GHz) interferometric synthetic aperture radar technology (InSAR) to obtain high-resolution (one arc-second) elevation data on a near-global scale for the purpose of generating the most complete digital topographic database of Earth. Rather than reflecting the “bald-earth” surface, an SRTM-derived digital elevation model (DEM) is unique in that it more closely reflects the elevation surface formed by vegetation (e.g., tree canopies) and anthropogenic features (e.g., buildings, towers, etc.). Assuming the elevation of the bald-earth surface is known, an estimate of the interferometric “scattering phase center height” (h_{spc}) can be computed (Brown, 2003; Brown & Sarabandi, 2003; Kellndorfer et al., 2004; Kobayashi et al., 2000; Saich et al., 2001). It follows that the value of h_{spc} is correlated with both the amount and height of vegetation present. Recent research has confirmed the feasibility of using SRTM DEMs together with bald-earth topography data to estimate the height of vegetation canopies (Brown, 2003; Brown & Sarabandi, 2003; Kellndorfer et al., 2004; Walker et al., 2007).

A second dataset with considerable potential to provide information on the horizontal structure of forests is the 2001 National Land Cover Dataset (NLCD; Homer et al., 2004). This multi-layer dataset, currently being developed by the Multi-Resolution Land Characteristics (MRLC) Consortium, uses an ecoregional mapping approach and consists of 1) normalized Tasseled Cap (TC) transformations of Landsat 7 ETM+ imagery from three time periods (early, peak, and late growing season), 2) classified land cover data derived from TC imagery, 3) independent image derivatives of imperviousness and tree canopy density, and 4) independent ancillary data layers including DEM derivatives of slope, aspect and elevation derived from the National Elevation Dataset (NED), which was seamlessly compiled for the entire United Sates for the first time in 1999. All data layers are being released at a grid spacing of 30 m.

A third and final dataset, also under active development, is the multi-partner Landscape Fire and Resource Management Planning Tools Project (LANDFIRE). LANDFIRE is an ecosystem, wildland fire, and wildland fuels mapping project designed to generate a comprehensive suite of spatial data layers describing wildland fuel, existing vegetation composition and structure, historical vegetation conditions, and historical fire regimes. A set of more than 20 national map products is being produced by LANDFIRE using the NLCD ecoregional mapping approach. Specific deliverables include maps of mean fire return interval, percent fire severity, and successional class, as well as existing vegetation type, canopy cover, and canopy height. The canopy height product is currently in development and is slated to be released as a discrete (i.e., five forested height classes) data layer. Aboveground biomass and carbon stocks are not being mapped as part of the LANDFIRE project. Consistent with the NLCD, all LANDFIRE data layers are being released at a grid spacing of 30 m.

The success of a mapping project such as the one proposed here depends largely on the availability of a suitable ground reference database. Complimenting the aforementioned assemblage of national spatial datasets is a national ground reference database available as part of the Forest Inventory and Analysis (FIA) program administered by the USDA Forest Service. In continuous operation since 1930, the FIA program is the only nationwide source of timely, consistent, and reliable forest inventory and monitoring information. The FIA Database (FIADB) contains plot-level forest biometric information collected repeatedly at more than 125,000 locations throughout the United States.

Given the highly complementary nature and quasi-synchronous development of the SRTM, NLCD, and LANDFIRE data sources, an exceptional opportunity exists for exploiting