Remote Sensing of Environment 194 (2017) 331–346

Contents lists available at ScienceDirect

Remote Sensing of Environment

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

Biomass retrieval from L-band polarimetric UAVSAR backscatter and PRISM stereo imagery

Zhiyu Zhang [a], Wenjian Ni [a,*], Guoqing Sun [b], Wenli Huang [b], Kenneth J. Ranson [c], Bruce D. Cook [c], Zhifeng Guo [a]

[a] *State Key Laboratory of Remote Sensing Science, Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences, Beijing 100101, China*
[b] *Department of Geographical Sciences, University of Maryland, College Park, MD 20742, USA*
[c] *Code 618, Biospheric Sciences Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA*

ARTICLE INFO

Article history:
Received 27 January 2016
Received in revised form 16 March 2017
Accepted 28 March 2017
Available online 10 April 2017

Keywords:
Forest biomass
Canopy height
Radar
UAVSAR
Prism
Stereo imagery
Incidence angle

ABSTRACT

The forest above-ground biomass (AGB) and spatial distribution of vegetation elements have profound effects on the productivity and biodiversity of terrestrial ecosystems. In this paper, we evaluated biomass estimation from L-band Synthetic Aperture Radar (SAR) data acquired by National Aeronautics and Space Administration (NASA) Uninhabited Aerial Vehicle SAR (UAVSAR) and the improvement of accuracy by adding canopy height information derived from stereo imagery acquired by Japan Aerospace Exploration Agency (JAXA) Panchromatic Remote Sensing Instrument for Stereo Mapping (PRISM) on-board the Advanced Land Observing Satellite (ALOS). Various models for prediction of forest biomass from UAVSAR data were investigated at pixel sizes of 1/4 ha (50 m × 50 m) and 1 ha. The variance inflation factor (VIF) was calculated for each of the explanatory variables in multivariable regression models to assess the multi-collinearity between explanatory variables. In addition, the *t*- and *p*-values were used to interpret the significance of the coefficients of each explanatory variables. The R^2, Root Mean Square Error (RMSE), bias and Akaike information criterion (AIC), and leave-one-out cross-validation (LOOCV) and bootstrapping were used to validate models. At 1/4-ha scale, the R^2 and RMSE of biomass estimation from a model using a single track of polarimetric UAVSAR data were 0.59 and 52.08 Mg/ha. With canopy height from PRISM as additional independent variable, R^2 increased to 0.76 and RMSE decreased to 39.74 Mg/ha (28.24%). At 1-ha scale, the RMSE of biomass estimation based on UAVSAR data of a single track was 39.42 Mg/ha with a R^2 of 0.77. With the canopy height from PRISM, R^2 increased to 0.86 and RMSE decreased to 29.47 Mg/ha (20.18%). The models using UAVSAR data alone underestimated biomass at levels above ~150 Mg/ha showing the saturation phenomenon. Adding canopy height from PRISM stereo imagery significantly improved the biomass estimation and elevated the saturation level in estimating biomass. Combined use of UAVSAR data acquired from opposite directions (odd and even tracks) slightly improved the biomass estimation. Combined use of UAVSAR data acquired from opposite directions (odd and even tracks) slightly improved the biomass estimation at 1/4-ha scale, R^2 increased from 0.59 to 0.66 and RMSE reduced from 52.08 to 48.57 Mg/ha. Averaging multiple acquisitions of UAVSAR data from the same look azimuth direction did not improve biomass estimation. A biomass map derived from NASA's LVIS (Laser Vegetation Imaging System) waveform data was used as a reference for evaluation of the biomass maps from these models. The study has also shown that the errors decreased when deciduous, evergreen, and mixed forests were modeled separately but the improvement was not significant.

1. Introduction

The ability to map forest aboveground biomass (AGB) at local to global scales from remote sensing is important since the biomass is closely related to the carbon storage of forests and the key to our understanding of the terrestrial carbon cycle (Houghton, 2005). Biomass retrieval from remote sensing data remains a challenging task, especially in areas with complex forest stand structure and variable environmental conditions (Lu, 2006; Sinha et al., 2015).

Radar waves can penetrate into forests and the backscattered signal is dependent on the amount and spatial distribution of water within the vegetation canopy. Early work on forest biomass estimation from SAR data have shown that radar backscattering of L-band HV polarization was clearly correlated with forest above-ground biomass up to 100–150 Mg/ha (LeToan et al., 1992; Ranson and Sun, 1994; Wang et al., 1995; Imhoff, 1995; Kasischke et al., 1995). The relationship between biomass and radar signature is not linear. Most studies (Ranson and Sun, 1994; Imhoff, 1995; Saatchi et al., 2007) have used logarithm of

---

* Corresponding author.
E-mail address: niwj@radi.ac.cn (W. Ni).

http://dx.doi.org/10.1016/j.rse.2017.03.034

biomass, while others used the cube root (Ranson and Sun, 2000) or square root (Robinson et al., 2013) of the biomass and the radar backscattering coefficient in dB in the biomass prediction models. In recent studies, various new parametric or non-parametric models were introduced. Tanase et al. (2014) compared results from forward parametric models based on the radiative transfer model such as the water cloud model (Attema and Ulaby, 1978), backward parametric models based on relationships of transformed biomass and radar backscattering intensity such as those mentioned above, and non-parametric models such as the ensemble regression (ER), random forest (RF) regression, and support vector machine (SVM) regression. They found that some parametric models consistently provided lower correlation between the observed and predicted biomass while nonparametric models generally provided an unbiased estimation. However, the biomass retrieval errors were largely similar for all parametric and nonparametric models studied.

Recent progress in the estimation of forest biomass from SAR and other remote sensing data is related to the extraction of additional forest parameters such as vertical structure. The data sources and methods for obtaining information on forest vertical structure include 1) Lidar point cloud (Bortolot and Wynne, 2005) and waveform data (Drake et al., 2002) capable of direct measurement of vertical structure of forest canopies; 2) Interferometric SAR data from which the canopy height can be retrieved (Cloude and Papathanassiou, 2003; Lavalle and Hensley, 2015; Lee and Fatoyinbo, 2015). The canopy height profile may also be estimated from polarimetric InSAR tomography (Tebaldini and Rocca, 2012); 3) high resolution optical stereo images (Hobi and Ginzler, 2012; Ni et al., 2014a; Motohka et al., 2015), from which a canopy height model can be generated; and 4) radargrammetry, from which canopy height can be derived from the point clouds in the same way as for optical stereo-pairs (Persson and Fransson, 2014; Rahlf et al., 2014; Solberg et al., 2015; Vastaranta et al., 2014; Yu et al., 2015). Motohka et al. (2015) used stereo images acquired by ALOS PRISM OB2 mode (the nadir and backward viewing images) to generate a Digital Surface Model (DSM). Then a digital canopy height model (DCHM) was obtained as the difference between the PRISM DSM and the 10 m digital terrain model (DTM) provided by the Geospatial Information Authority of Japan (GSI). They found that DCHM values exhibited a significant correlation with AGB. In Ni et al. (2014a), three pairs of stereo images formed by PRISM triplets were used to generate three point cloud datasets at the same location, which were then co-registered to form one higher density point cloud dataset. Their results shown that the mean height of points at 30 m grid size from the denser point clouds was highly correlated to the height indices derived from lidar waveform data in the same grid.

The sigmoid relationship between radar backscatter and forest biomass and the complex forest spatial structure limit the sensitivity of SAR backscatter to biomass at higher biomass levels. Studies (Saatchi et al., 2011; Sun et al., 2011; Ni et al., 2014b) have shown that incorporation of vertical forest structural parameters with SAR intensity data in forest biomass mapping improved the estimation accuracy and significantly reduced saturation-related issues. In Ni et al. (2014b), penetration depth, the difference between canopy height from stereo imagery and height of scattering phase center (HSPC) from interferometric SAR data was introduced in the model-based look-up table inversion and played an important role in the biomass estimation. Saatchi et al. (2011) and Sun et al. (2011) showed significant contributions of the height of scattering phase center from InSAR in biomass estimation models using L-band SAR backscatter.

Optical stereo images are now available globally at high resolution. Global coverage of PRISM was acquired during 2007–2010 by ALOS/PRISM.The launch of spaceborne high-resolution stereo sensors, the maturation of photogrammetry theory and the development of fully digital and automatic image processing during the last decade have made the application of photogrammetric methods easier. Research on estimation of forest structure using optical stereo imagery has become more active in recent years e.g., Ni et al. (2014a) for canopy height estimation and Amini and Sumantyo (2009) for SAR and optical image texture. However the performance of combined use of SAR backscatter and canopy height from optical imagery has not been evaluated in detail yet.

This study demonstrates, for the first time, the improvement in above ground biomass estimation that can be realized with the powerful combination of L-band SAR backscatter and 3D height recovery from stereo-optical based point cloud data. This study is a step further in regional/global mapping of forest biomass in high resolution by combined use of L-band radar backscatter and optical stereo images.

The multi-polarization, multi-angle and multi-acquisition L-band SAR data from UAVSAR provides a high quality dataset for exploring the capability and limitation of SAR data to estimate forest biomass, and evaluate the benefits from incorporation of canopy height information from stereo imagery in biomass estimation models. Studies described in Robinson et al. (2013) have demonstrated that the variability in estimated biomass decreased substantially at larger plot sizes (>0.5 ha). A stability of field-estimated biomass at scales of about 1.0 ha has been suggested. Ahmed et al. (2014) investigated the uncertainties of biomass estimation from UAVSAR HV backscatter and found that the error of the biomass prediction model was larger than the total measurement error caused by image speckle and calibration, and biomass allometric equations at hectare scales, while at 25 m × 25 m scale the measurement error dominated. In this study, regression models for biomass estimation using various variables from UAVSAR data are developed at 50 m × 50 m (1/4 ha) and 100 m × 100 m pixel sizes. The effects of spatial resolution, look direction, as well as forest types on the mapping accuracy of biomass are investigated. Leave-one-out cross-validation and bootstrapping are used to test the performance and assess the errors of the regression models. The mapping accuracies are evaluated by adding the canopy height from PRISM data. LVIS waveform data are acquired a few days apart from UAVSAR flights were used to generate the biomass map (Huang et al., 2013). The map is used as reference to assess the biomass maps generated from UAVSAR and PRISM data.

2. Materials

2.1. Test sites and field plots

The forests in the study area form a transition between boreal and temperate biomes. Encompassing an area of about 20 km × 100 km (Fig. 1), the Northern Experimental Forest (NEF) near Howland, Maine (ME) (45.25°N, 68.75°W), and the USDA-Forest Service Penobscot Experimental Forest (PEF) near Bradley, ME (44.8°N, 68.6°W) are long term research sites. Topographically, the region varies from flat to gently rolling, with a maximum elevation change of <135 m. Due to the region's glacial history, soil drainage classes within a small area may vary widely, from excessively drained to poorly drained. Consequently, an elaborate patchwork of forest communities has developed, supporting exceptional diversity in forest spatial structure and tree species (Ranson and Sun, 1994). In 2009, twenty-four plots (50 m × 200 m per plot, each plot being divided into sixteen 25 m × 25 m subplots) in the NEF and PEF were sampled in a field campaign. Ten 50 m × 100 m and one 50 m × 50 m plot was measured at NEF in 2010.

2.2. UAVSAR data

UAVSAR (http://uavsar.jpl.nasa.gov) was specifically designed to acquire airborne repeat track SAR data for differential interferometric measurements (Rosen et al., 2006). UAVSAR provides high resolution polarimetric SAR data for use on multiple studies. UAVSAR is a well-calibrated SAR system for polarimetric applications (Fore et al., 2015). Corner reflectors were used for absolute radiometric calibration, channel imbalance and phase error correction. The cross-talk calibration was