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Remote Sensing of Environment 102 (2006) 63 – 73
Remote Sensing of Environment
www.elsevier.com/locate/rse

Mapping forest structure for wildlife habitat analysis using multi-sensor (LiDAR, SAR/InSAR, ETM+, Quickbird) synergy

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Received 9 September 2005; received in revised form 24 January 2006; accepted 30 January 2006

Abstract

Measurements of forest structure are important for wildlife habitat management. An optimal strategy for mapping forest structure would include detailed measurements of the vertical dimension, which are traditionally provided by field sampling, together with the broad spatial coverage afforded by remote sensing. While no single sensor is capable of delivering this at the present time, it should be possible to combine information from multiple sensors to achieve a reasonable approximation. In this study, we compare estimates of forest structural metrics derived from remote sensing to measurements obtained in the field (large tree maximum canopy height, mean canopy height, standard deviation canopy height, and biomass). We then statistically combine structural information from LiDAR, RaDAR, and passive optical sensors in an attempt to improve accuracy of our estimates. The results of this study indicate that LiDAR is the best single sensor for estimating canopy height and biomass. The addition of ETM+ metrics significantly improved LiDAR estimates of large tree structure, while Quickbird and InSAR/SAR improved estimates either marginally or not at all. The combination of all sensors was more accurate than LiDAR alone, but only marginally better than the combination of LiDAR and ETM+. Structure metrics from LiDAR and RaDAR are essentially redundant, as are ETM+ and Quickbird.

Keywords: LiDAR; RaDAR; SAR; InSAR; Fusion; Habitat; Forest structure; Canopy height; Biomass

1. Introduction

Measurements of forest structure are critical for many applications, including wildlife management and biodiversity studies, fire modeling, and carbon stock estimation. Canopy height and associated metrics of vertical heterogeneity (North et al., 1999), when considered together with site characteristics, are indicators of old-growth forest conditions and thus are of interest to researchers studying old-growth endemics. Canopy height is an important input for ecosystem and fire models and is highly correlated with biomass. Biomass is a key component of the carbon cycle, as forests represent large carbon sources and sinks (Skole & Tucker, 1993), and is also a surrogate for fuel loading estimation (Finney, 1998). Large trees, in particular, may provide essential habitat to California spotted owls (North et al., 1999) and are an important component of aboveground biomass.

Traditionally, these attributes have been measured in the field using hand-held equipment. Field-based methods can be highly accurate but are time-consuming and thus are typically limited in scope to either mapping at fine scales or sampling at the landscape scale. Multispectral (Hyyppä et al., 1998) and hyperspectral remote sensing (Pu & Gong, 2004) have been used to map structural metrics at moderate resolution and broad scales. However, passive optical sensors have difficulty penetrating beyond upper canopy layers (Weishampel et al., 2000) and are better suited for mapping horizontal structure, e.g., land cover type. Interferometric synthetic aperture radar (InSAR) can provide measures of vertical structure at

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0034-4257/$ - see front matter
doi:10.1016/j.rse.2006.01.021

landscape scales at varying degrees of accuracy; however, at the present time these are best suited for structurally homogeneous forest types (Treuhaft & Cloude, 1999; Treuhaft & Siqueira, 2000). Full waveform-digitizing, large footprint LiDAR provides highly accurate measurements of forest structure at the footprint level of observation (Nelson et al., 1984, 1988; Nilsson, 1996; Lefsky et al., 1999a; Drake et al., 2002; Hyde et al., 2005); however, they are not capable of imaging entire landscapes. Due to the high cost of flight time, the need to limit scanning to near nadir in order to prevent ranging errors, and the presence of coverage gaps due to aircraft pitch and roll, a typical large footprint LiDAR mission acquires samples (albeit at a high frequency) instead of the wall-to-wall coverage provided by other sensors, such as RaDAR or passive optical sensors.

The optimal strategy for mapping forest structure would include the finely detailed measurements of the vertical dimension that field sampling provides as well as the broad spatial coverage of remote sensing. Although no single technology is currently capable of providing this level of forest structural information, advancements in InSAR and LiDAR will likely lead to broad-scale mapping of vertical structure in the near future. In the meantime, it is possible to map forest structure at intermediate scales by statistically combining or fusing information from multiple sensors to take advantage of the highly detailed vertical measurements provided by full waveform-digitizing LiDAR, the broad-scale mapping capabilities of passive optical sensors, and the coarse sensitivity to horizontal and vertical structure afforded by InSAR. Combining information from multiple sensors, or data fusion, has yielded promising results for the estimation of forest structural characteristics (Wulder et al., 2004). Hudak et al. (2002) combined regression and co-kriging models from LiDAR and multispectral data; the results were more accurate than either data set alone. Wulder and Seeman (2003) used texture metrics from Landsat TM images to improve LiDAR estimates of canopy height (from 61% to 67% variability explained). Moghaddam et al. (2002) found that combining Landsat TM and several RaDARs was more accurate in predicting ground-based measurements of forest structure than any single sensor alone. Slatton et al. (2001) combined LiDAR data with interferometric RaDAR to improve the estimates of vegetation heights.

1.1. Objectives

Previous work (Hyde et al., 2005) established that large footprint, waveform LiDAR could be used to map forest structure within our study area at the footprint level with a high degree of accuracy. LiDAR was also highly accurate at measuring maximum canopy height and biomass at the "stand" (defined as 1 ha) level of observation when at least 40% of the area of observation was sampled. Where LiDAR data are sparse, it is an open research question whether or not improvements can be made at the stand and landscape scales via the combination of data from multiple sensors. For this study, only large diameter (>76 cm dbh) trees will be considered because at the stand level only stems in this size class were measured during our field data collection. Furthermore, a comparison at the footprint level of observation is somewhat problematic due to the inconsistent geolocation accuracy and resolution of the various sensors used in this study.

The primary objective of this effort is to quantify and compare the predictive power of individual remote sensing data sets to estimate large tree canopy height and biomass at the landscape scale. The secondary objective is to combine large footprint, waveform LiDAR data with other remote sensing data sets to determine if there is either synergy or redundancy in predictive power when combining other remote sensing data sets and large footprint, waveform LiDAR data. The tertiary objective is to ascertain the optimal sampling regime for large footprint, waveform LiDAR, i.e., to determine how sparsely large footprint, waveform LiDAR can be sampled (and fused with other remote sensing data sets) and still achieve a reasonable degree of predictive power. The results will be used to create landscape scale maps of forest structure suitable for wildlife habitat analysis.

The paper is organized as follows. First we describe collection of field plot data and provide details of the remote sensing (LVIS, SAR/InSAR, ETM+, Quickbird, DEM) data acquisition, which took place over the Sierra Nevada. This is followed by a presentation of the methods used in the processing and analysis of both remote sensing and field data, including the estimation of canopy height and biomass. We then present the results of statistical comparisons between field-derived and remote sensing-derived forest structural attributes and the results of multi-sensor fusion. Finally, we discuss the significance of results relative to the retrieval of forest structure at the landscape level.

2. Data collection

The data used in this study include in situ observations of forest structure, LiDAR data sets (Hyde et al., 2005), and other remote sensing data sets (Fig. 1).

2.1. Site description

The study area is located in the Sierra Nevada mountains of California. This site is approximately 60,000 ha, with elevation ranging from 853 to 2743 m. Forest types include white fir (*Abies concolor*), red fir (*Abies magnifica*), Sierran mixed-conifer, ponderosa pine (*Pinus ponderosa*), giant sequoia (*Sequoiadendron giganteum*), and montane hardwood-conifer (for a complete description, see Hunsaker et al., 2002).

2.2. Field data

One hundred twenty plots were distributed through the northern part the study area (Sierra National Forest) using a modified stratified random sampling scheme. Although the plots were centered on laser footprints, the actual waveforms were not examined before the stratification (to prevent bias). Hence, no attempt was made to retain only waveforms that