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Fusion of LiDAR and imagery for estimating forest canopy fuels

Todd L. Erdody [1], L. Monika Moskal *

Remote Sensing and Geospatial Analysis Laboratory and Precision Forestry Cooperative, School of Forest Resources, College of the Environment, University of Washington, Seattle WA 98195-2100, United States

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ABSTRACT

Due to increased fuel loading as a result of fire suppression, land managers in the American west are in need of precise information about the fuels they manage, including canopy fuels. Canopy fuel metrics such as canopy height (CH), canopy base height (CBH), canopy bulk density (CBD) and available canopy fuel (ACF) are specific inputs for wildfire behavior models such as FARSITE and emission models such as FOFEM. With finer spatial resolution data, accurate quantification of these metrics with detailed spatial heterogeneity can be accomplished. Light Detection and Ranging (LiDAR) and color near-infrared imagery are active and passive systems, respectively, that have been utilized for measuring a range of forest structure characteristics at high resolution. The objective of this research was to determine which remote sensing dataset can estimate canopy fuels more accurately and whether a fusion of these datasets produces more accurate estimates. Regression models were developed for ponderosa pine (*Pinus ponderosa*) stand representative of eastern Washington State using field data collected in the Ahtanum State Forest and metrics derived from LiDAR and imagery. Strong relationships were found with LiDAR alone and LiDAR was found to increase canopy fuel accuracy compared to imagery. Fusing LiDAR with imagery and/or LiDAR intensity led to small increases in estimation accuracy over LiDAR alone. By improving the ability to estimate canopy fuels at higher spatial resolutions, spatially explicit fuel layers can be created and used in wildfire behavior and smoke emission models leading to more accurate estimations of crown fire risk and smoke related emissions.

1. Introduction

In the American west, increased ground and canopy fuel loading as well as forest structure change due to fire suppression, timber management and climatic effects (Running, 2006; Schmidt et al., 2002) has amplified the frequency and extent of crown fires (Agee, 1993). Wildfires are major producers of CO_2 (carbon dioxide), CO (carbon monoxide) and $PM_{2.5}$ (particulate matter smaller than 2.5 µm diameter) which are harmful to human health (Hardy et al., 2001). For predicting the initiation and propagation of crown fires in wildfire behavior modeling as well as estimating emissions, accurate canopy fuel information is required. Improved emission estimates from wildfires are necessary to estimate the impacts of these pollutants on human health and the environment (Battye & Battye, 2002).

Remote sensing technologies such as airborne LiDAR (Light Detection and Ranging) and aerial imagery are high spatial resolution systems that can effectively improve estimates of canopy fuel metrics for wildfire behavior modeling and reflect the true spatial heterogeneity of the forest. These metrics are canopy height (CH), canopy base height (CBH), canopy bulk density (CBD) and available canopy fuel weight (ACF). Semiempirical wildfire behavior modeling programs such as FARSITE (Finney, 1998) and FlamMap (Finney, 2006) utilize spatial data including fuels, topography and weather to predict wildfire growth and crown fire initiation and propagation. Currently, most of these inputs are derived from layers of coarse resolution which lead the pixels to be spatially homogeneous (Finney & Andrews, 1994).

Previous estimates of canopy fuel metrics have been derived through the Landscape Fire and Resource Management Planning Tools Prototype Project (LANDFIRE), a nationwide effort to map fuels and vegetation at 30 m resolution for use by fire and landscape managers (Rollins & Frame, 2006). For data layers created for LANDFIRE, canopy fuel values of CBD and CBH were modeled based on Landsat imagery, biophysical characteristics and topographic characteristics. Since passive sensors cannot detect canopy depth well, the models have low accuracy and tend to underestimate both CBD and CBH (Keane et al., 2006). While these datasets are useful for general landscape level fuel information, other datasets built on a local scale with greater accuracy should be utilized to complement LANDFIRE data or replace it completely (Reeves et al., 2006). By utilizing localized high resolution data instead of LANDFIRE data, more realistic estimations

* Corresponding author. Tel.: +1 206 221 6391.
E-mail address: lmmoskal@uw.edu (L.M. Moskal).
[1] Now at National Park Service, Southern Cascades Network, Klamath Falls, OR 97601, United States.

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of fire spread can be achieved (Krasnow et al., 2009) thus modeling these fuel metrics at higher resolutions should increase estimation accuracy and reduce model sensitivity.

For this research, discrete-return airborne LiDAR and high resolution color near-infrared imagery was used to estimate canopy fuel metrics in a ponderosa pine and transitional mixed conifer forest of eastern Washington State. A double sampling approach using regression models was utilized for ease of use and broad-scale applicability using easily available analytical tools. LiDAR and imagery data were used to create regression models in 3 different combinations: LiDAR only, imagery only and LiDAR and imagery fusion.

1.1. Remote sensing of canopy fuels

Canopy fuel metrics are difficult to measure for a number of reasons. For uniform forest stands, it is assumed that canopy biomass is uniformly distributed vertically, but this assumption does not hold true in a complex forest stand. This is due to multiple layers in the canopy, presence of ladder fuels and variation within tree species and within the forest stand. Although destructive sampling is the most accurate way to measure canopy fuels, it is not a desirable or effective way of acquiring data.

Remote sensing technologies, including LiDAR (discrete-return and full-waveform) and imagery (aerial and satellite) have been used to estimate canopy fuel metrics. Some of the LiDAR and imagery-derived forest structure characteristics can be used as spatially explicit data inputs for fire modeling software. Previous research suggests that LiDAR-derived canopy metrics, used as data layers in FARSITE, could serve as a more realistic prediction of fire spread and intensity (Andersen et al., 2005).

In the context of forest fuels, imagery has mainly been utilized to determine fuel types through aerial photo interpretation (Bertolette & Spotskey, 1999; Scott et al., 2002) and Landsat image classification (Kourtz, 1977; Van Wagtendonk & Root, 2003). For high resolution sensors such as Quickbird and IKONOS, an object-based classification approach has been used to delineate fuel types due to the fact that the resolution is smaller than the objects of interest (Arroyo et al., 2006). In forest inventory applications, both satellite and aerial optical imagery have been proven to be good estimators of stand density, volume and canopy height (De Wulf et al., 1990).

In terms of canopy fuel modeling and mapping, a variety of spatial and spectral sensors has been utilized. Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) imagery has been used to map fuel models and canopy bulk density in the conifer forests of northern Idaho (Falkowski et al., 2005) while Landsat imagery has been utilized for estimating canopy fuel metrics for the LANDFIRE database (Rollins & Frame, 2006). Hyperspectral imagery in the form of the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) has been used to estimate canopy cover and tree species fraction in the ponderosa pine (*Pinus ponderosa*) and Douglas-fir (*Pseudotsuga menziesii*) forests of Colorado (Jia et al., 2006). Although imagery from these low to medium resolution sensors has been used for a variety of canopy fuel attributes, canopy fuels have not been estimated using sub-meter resolution imagery.

Some structural parameters of forests are often measured through another important imagery derivative, image texture. Texture is a statistical measure of the variation of the spectral response within an image and is used through applying occurance and co-occurance matrices to an image (Haralick, 1979). Since texture is measuring the spectral and spatial variation of the pixels, which are affected by tree crown dimensions, it is similar to measuring the roughness of the canopy. Biomass estimations have been made using image texture (Wulder et al., 1998) as well as classification of species composition and land cover types (Franklin et al., 2000) and forest structure for individual tree canopies and forest stands (Moskal & Franklin, 2002).

Although utilizing imagery has the benefit of being easily available, expertise is required for image interpretation, the costs for specific software are high and imagery does not capture what is beneath the main canopy (Arroyo et al., 2008). What is needed is a sensor that can see through the canopy and represent the three-dimensional structure of the forest.

The use of small-footprint (discrete-return) airborne LiDAR remote sensing technology includes applications for forestry by measuring various forest structure characteristics in three dimensions. By allowing laser pulses to penetrate below the canopy, reconstruction of the canopy can be achieved. LiDAR has been shown to measure forest structure characteristics accurately in a variety of forest types. For example, tree heights were measured in Switzerland in a mixed conifer forest (Morsdorf et al., 2004), canopy base heights in Sweden (Holmgren & Persson, 2004), crown volume in Spain (Riano et al., 2004), biomass in Washington and Alaska (Li et al., 2008), leaf area index (LAI) in heterogeneous urban forest (Richardson et al., 2009), forest stand characteristics in Oregon (Means et al., 2000) and Colorado (Hall et al., 2005) and canopy fuel loading and canopy bulk density in Yellowstone National Park (Halligan, 2007). Similarly, canopy fuel metrics (CH, CBH and CBD) have been estimated in mixed conifer/deciduous forests of Germany (Riano et al., 2003) and in Western Washington State (Andersen et al., 2005). Canopy base heights have been estimated using a voxel-based approach (Popescu & Zhao, 2008). While most of these studies were done on plot or stand scale, some obtained measurements at tree scale (Coops et al., 2004; Riano et al., 2004), while others measured both (Halligan, 2007).

Digital true color and false color near-infrared aerial imagery have been used extensively for forest inventory and health monitoring and the advancement of digital aerial imagery has extended the possibilities of using it in conjunction with other digital data sources such as LiDAR. LiDAR alone cannot provide all the information about the canopy that is desired. Although LiDAR can accurately assess biomass and height metrics, the technology cannot discern tree species very well, unless fused with optical sensors (Perrson et al., 2004). By building on the strengths of each sensor, a fusion of the two could potentially improve canopy fuel estimations.

Studies have shown that a fusion of LiDAR and high resolution optical imagery can improve accuracy of tree crown metrics (McCombs et al., 2003; Popescu & Wynne, 2004). LiDAR data, used in a height bin approach in conjunction with Quickbird imagery showed an increase in accuracy of fuel type mapping in Texas (Mutlu et al., 2008a). Fuel type mapping was also achieved using a fusion of LiDAR and AVIRIS data in Hawaii (Varga & Asner, 2008). Utilizing the broad spatial coverage of Landsat Enhanced Thematic Mapper Plus (ETM+) data and the high spatial resolution of LiDAR, regression and kriging methods were used to estimate and map canopy height (Hudak et al., 2002). Forest height estimates using a fusion of LiDAR and IKONOS data using a least-squares linear regression model were found to be significant (Donoghue & Watt, 2006). Fuel maps created from a LiDAR/imagery fusion have shown to be more accurate than maps created from imagery alone and when used in FARSITE, produce different fire perimeters and growth area (Mutlu et al., 2008b).

Although different in many aspects, other studies have utilized full-waveform LiDAR and interferometric synthetic aperture radar (InSAR) for the estimation of forest metrics. By fusing full-waveform LiDAR data with either 30 m resolution Landsat, 2 m resolution Quickbird imagery or InSAR, attributes of canopy height and biomass are moderately improved than by LiDAR data alone (Hyde et al., 2006). By using InSAR alone, height estimations can be achieved with slightly larger error rates but at lower cost than LiDAR (Andersen et al., 2008; Breidenbach et al., 2008).

By defining canopy fuels heterogeneously, more accurate assessments of canopy fuels can be achieved by utilizing high resolution remote sensing technologies. Fire managers will be able to make