ESTIMATING FOREST CROWN FUEL VARIABLES USING LIDAR DATA

Hans-Erik Andersen
Precision Forestry Cooperative
University of Washington
College of Forest Resources
Seattle, WA 98195
hanserik@u.washington.edu

Robert J. McGaughey
Stephen E. Reutebuch
Ward W. Carson
PNW Research Station
USDA Forest Service
Seattle, WA 98195
bmcgaughey@fs.fed.gov
sreutebuch@fs.fed.gov
wcarson@fs.fed.gov

Gerard F. Schreuder
Precision Forestry Cooperative
University of Washington
College of Forest Resources
Seattle, WA 98195
gsch@u.washington.edu

ABSTRACT

Fire researchers and managers are dependent upon accurate, reliable, and efficiently-obtained data for the development and application of crown fire behavior models. In particular, reliable estimates of critical forest canopy structure characteristics, including canopy bulk density, stand height, canopy fuel weight, and canopy base height, are required to accurately map fuel loading and model fire behavior over the landscape. The use of airborne laser scanning (LIDAR), a high-resolution active remote sensing technology, provides for accurate and efficient estimation of crown fire behavior variables over extensive areas of forest. In this study, estimates of crown fire behavior variables were developed from the spatial distribution of the small-footprint, discrete-return LIDAR data acquired over stands of varying condition within Capitol State Forest, in western Washington State. Using regression analysis, these LIDAR-based estimates were compared to field-based crown fuel estimates generated from inventory plot data. Results indicate that LIDAR can be used to develop maps of critical crown fire variables over forest areas in the Pacific Northwest. Canopy fuel estimates were generated for each grid cell area (30 m × 30 m) over the extent of the study area.

INTRODUCTION

Accurate estimates of stand height, canopy base height, canopy bulk density, and total canopy fuel weight would improve the data layer creation process for wildfire simulation models such as FARSITE (Finney, 1998) or future fire spread models. Previously, these data layers were generated using the output from stand-level growth models such as the Forest Vegetation Simulator (FVS), which depend upon a tree list to drive the simulations (Teck *et al*., 1996, Wykoff *et al.*, 1982). Since the stand-level estimates generated from these models are based upon a relatively sparse sample of inventory attributes, they will be subject to sampling error and will be unable to capture variability in stand structure at finer spatial scales over the landscape. If such variables could be accurately estimated using remotely-sensed data, in a spatially explicit format, the application of fire spread models to landscapes would be significantly improved.

The emergence of a new generation of active, high-resolution remote sensing systems could potentially allow for more accurate and efficient estimation of canopy fuel characteristics over the landscape. In particular, the ability of active infrared laser scanning (LIDAR) systems to acquire direct, three-dimensional measurements of canopy structure could significantly improve estimates of the quantity and distribution of canopy biomass. Previous studies have shown that LIDAR can be used to estimate a variety of forest inventory parameters, including biomass, stem volume, stand height, basal area, and stand density (Naesset, 1997a; Naesset, 1997b; Means *et al.*, 2000). A recent study presented a conceptual approach to estimating fire behavior variables (including canopy bulk density and canopy base height) using last-return LIDAR data, but this study did not compare results to field-based estimates, so it is difficult to evaluate the methodology (Riano *et al.*, 2003). In this paper, we present and evaluate an approach to estimating several critical canopy fuel metrics, including canopy fuel weight, canopy bulk density, canopy base height, and stand height, using high-density, multiple-return LIDAR data in a Pacific Northwest conifer forest.

STUDY AREA

The study area for this investigation was a 5.2 km^2 area within Capitol State Forest, Washington State, USA. This forest is primarily composed of coniferous Douglas-fir (*Pseudotsuga menziesii*) and western hemlock (*Tsuga heterophylla*) and, to a lesser degree, hardwoods such red alder (*Alnus rubra*) and maple (*Acer spp.*). The extent of the study area is shown in Figure 1. This site is the location of an ongoing experimental silvicultural trial, and contains coniferous commercial forest stands of varying age and density. An extensive topographic survey was conducted throughout the area to enable rigorous evaluation of a variety of technologies relevant to precision forest management, including high-resolution remote sensing and terrestrial geopositioning systems.

A total of 104 fixed area field inventory plots were established over a range of stand conditions. Plot sizes ranged from 0.04 to 0.5 acres. Measurements acquired at each plot included species and diameter at breast height (DBH). In addition, total height and height-to-base-of-live-crown were measured on a selection of trees. The data from this selection were used to build regression models for estimating height and crown ratio for all plots within the study area.

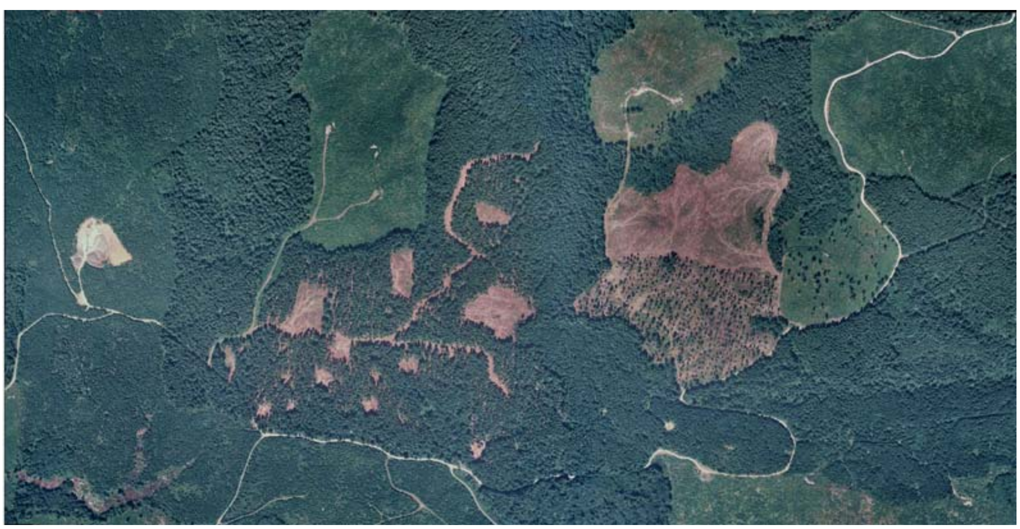

Figure 1. Orthophoto of Capitol State Forest study area in Washington State. (Courtesy of Washington State Department of Natural Resources, Resource Mapping Section).

LIDAR DATA

High-density LIDAR data were acquired over the study area with a SAAB TopEye* system mounted on a helicopter platform in March, 1999. The system settings and flight parameters are shown in Table 1. The vendor provided "filtered ground" data that were used to generate a 5-ft digital terrain model, with a mean error of 0.22 ± 0.24 m (Reutebuch *et al*. 2003). The LIDAR data included up to four returns from each laser pulse. The elevations of the LIDAR measurements were converted to heights by subtracting off the elevation of the underlying terrain.

Flying height	200 m
Flying speed	25 m/s
Swath width	70 m
Forward tilt	8 degrees
Laser pulse density	3.5 pulses/m^2
Laser pulse rate	7000 Hz

FIELD-BASED FUEL ESTIMATES

Field-based estimates of canopy fuels were generated using the methodology developed for the Fire and Fuels Extension to the Forest Vegetation Simulator (FFE-FVS) (Beukema *et al*. 1997). In this approach, the foliage of each tree is estimated using the equations developed by Brown and Johnson (1976). These equations generate estimates of the total dry weight of live and dead material for each individual tree crown, and provide a break-down of the proportion of the total crown weight that is associated with foliage and different size classes of branchwood. Following the methodology of Scott and Reinhardt (2001), crown fuels are defined as foliage and fine branchwood (50 percent of the 0 to 0.25 inch diameter branchwood). These crown weight equations can then be used to generate total crown fuel weight estimates for each tree in a plot given a tree list with information including species, DBH, crown ratio, and crown class. It should be noted that since crown class was not collected for all plots used in this study, crown weight could not be adjusted for relative dominance of the tree within the stand.

In this model, it is assumed that the crown material on each tree crown is evenly distributed along a crown's length. In order to generate an aggregate measure of canopy bulk density at the plot level, the total fuel weight for all trees within the plot are summed at 1-foot increments from the ground to the top of the tallest tree. The canopy bulk density is then defined as the maximum 15-foot running mean of crown fuel density within the plot. Following Scott and Reinhardt (2001), canopy base height is calculated as the lowest height at which the canopy fuel density exceeds a critical threshold (0.011 kg/m^3). Analogously, stand height is defined as the highest height at which the canopy fuel density is greater than 0.011 kg/m^3. Using this methodology, estimates of canopy fuel weight, canopy bulk density, canopy base height, and stand height were generated for each plot within the study area.

LIDAR-BASED FUEL ESTIMATES

Previous studies have developed strong regression relationships between plot-level LIDAR-based metrics and a number of forest inventory parameters, including biomass, stem volume, basal area, height, and stem density (Means et al., 2000; Naesset and Bjerknes, 2001). Naesset and Bjerknes (2001) used a limited number of LIDAR-based predictor variables, including the maximum (h_{max}), mean (h_{mean}), and coefficient of variation (CV) of the LIDAR heights, several quantile-based metrics describing the LIDAR height distribution (25th (h_{25}), 50th (h_{50}), 75th (h_{75}), and 90th (h_{90}) percentile heights), and a density metric (D) (percentage of first returns within the canopy) to estimate tree heights and stem density within young stands in Norway. It was expected that this pool of independent variables will collectively provide a concise description of canopy structure within the plot area, and therefore could also be used to estimate other

* The use of commercial names is for the convenience of the reader and does not imply any endorsement by the USDA Forest Service or the University of Washington.

structural metrics such as canopy fuel weight, canopy bulk density, canopy base height, and stand height. A program was written in IDL (Research Systems Inc. Interactive Data Language) which extracted the LIDAR data within each plot area and calculated these seven metrics from the distribution of LIDAR heights. This list of plot-level LIDAR metrics was then merged with the plot-level field estimates in a single text file and imported into S-Plus, a statistical software package. A stepwise regression procedure within S-Plus was used to identify possible models for estimating each dependent variable, although an emphasis was placed upon developing parsimonious, structural models and minimizing correlation between independent variables.

RESULTS

Canopy fuel weight

Residual plots for canopy fuel weight prediction indicated unconstant error variance, therefore a logarithmic transformation of canopy fuel weight was used to stabilize the variance. The final model identified via regression analysis for estimating canopy fuel weight took the following form:

$$\ln(\textit{canopy fuel weight}) = 7.52 + (-0.0311)h_{mean} + (0.0356)h_{25} + (2.3452)D$$

where D is the percentage of LIDAR first returns from the canopy (above 2 meters in height)

This model had a coefficient of determination of 0.86. . It should be noted that in this context the coefficient of determination (R^2) represents the percentage of variability explained by the regression relationship in the linearized space resulting from the transformation, not in the original scale, so this measure should be interpreted with caution. A scatterplot of the field-based versus predicted LIDAR-based plot-level measures of (log-transformed) canopy fuel weight is shown in Figure 2.

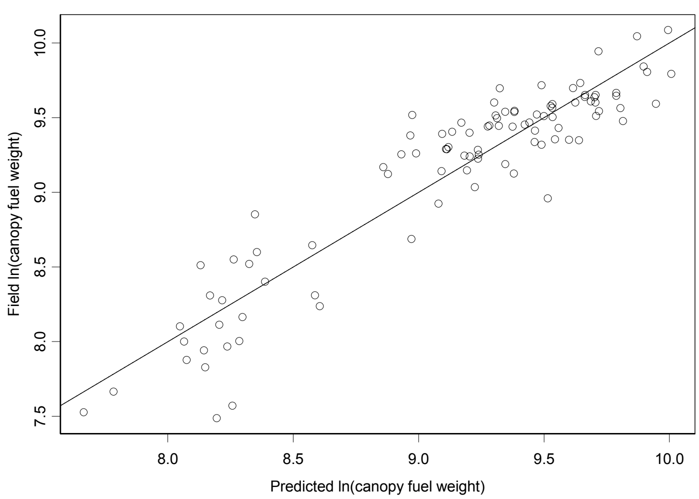

Figure 2. Field-measured versus predicted (log transformed) foliage weight (R^2 = 0.86). Line shows 1:1 relationship.

Canopy bulk density

A log transform of canopy bulk density was also used to stabilize the variance. The final model identified via regression analysis for estimating canopy fuel weight took the following form:

$$\ln(\textit{canopy bulk density}) = -3.2995 + (-0.0674)h_{mean} + (0.0648)h_{25} + (2.2407)D$$

This model had a coefficient of determination of 0.81. A scatterplot of the field-based versus predicted LIDAR-based plot-level measures of (log-transformed) canopy bulk density is shown in Figure 3.

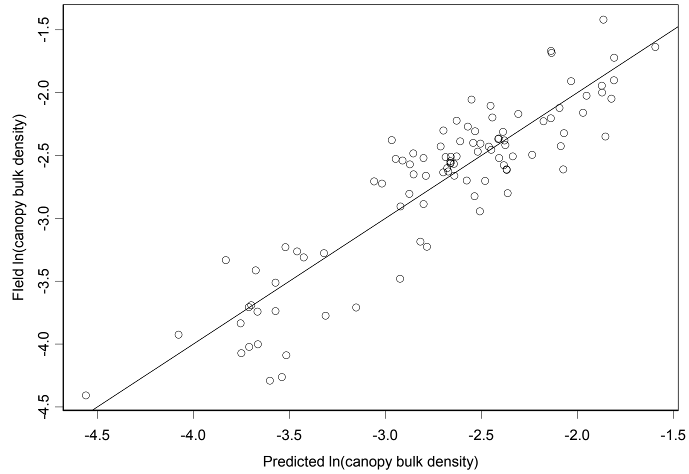

Figure 3. Field-measured versus predicted (log transformed) canopy bulk density (R^2 = 0.81). Line shows 1:1 relationship.

Canopy base height

The final model identified via regression analysis for estimating canopy base height took the following form:

$$Canopy\ base\ height = 22.68 + (0.7753)h_{25} + (-34.7814)D$$

This model had a coefficient of determination of 0.84. A scatterplot of the field-based versus predicted LIDAR-based plot-level measures of canopy base height is shown in Figure 4.

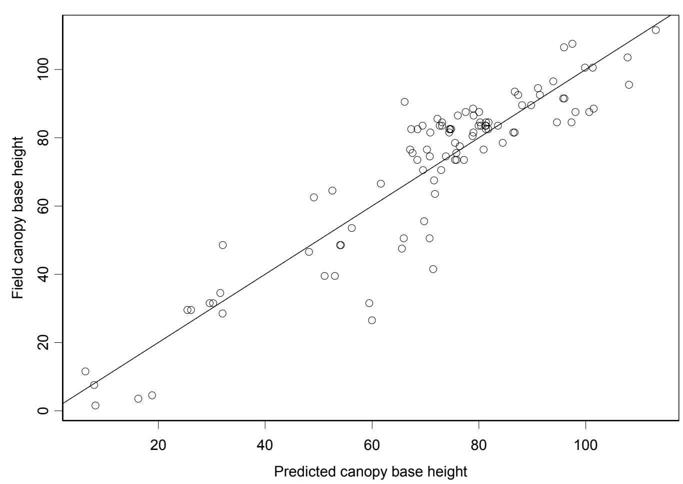

Figure 4. Field-measured versus predicted canopy base height (R^2 = 0.84). Line shows 1:1 relationship.

Stand height

The final model identified via regression analysis for estimating stand height took the following form:

$$Stand\ height = 8.0512 + (1.0006)h_{90} + (13.6252)D$$

This model had a coefficient of determination of 0.98. A scatterplot of the field-based versus predicted LIDAR-based plot-level measures of stand height is shown in Figure 5.

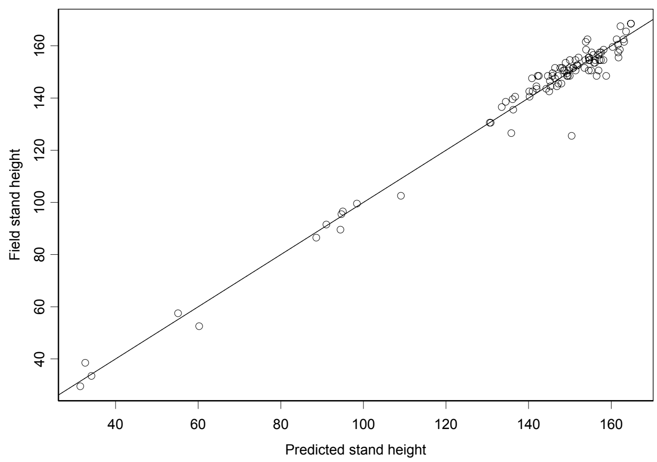

Figure 5. Field-measured versus predicted stand height ($R^2 = 0.98$). Line shows 1:1 relationship.

Mapping canopy fuels

After regression models have been developed to establish a functional relationship between the LIDAR data and the canopy fuel measures, these equations can be used to generate maps of canopy fuel characteristics over the entire extent of the LIDAR data coverage. Figures 6 – 9 show maps of stand height, canopy fuel weight, canopy bulk density, and canopy base height over the Capitol Forest study area, with measurements provided at a 30 × 30 meter grid cell resolution. It should be noted that canopy base heights were given a value of 200 ft if no canopy vegetation was present in the grid cell area.

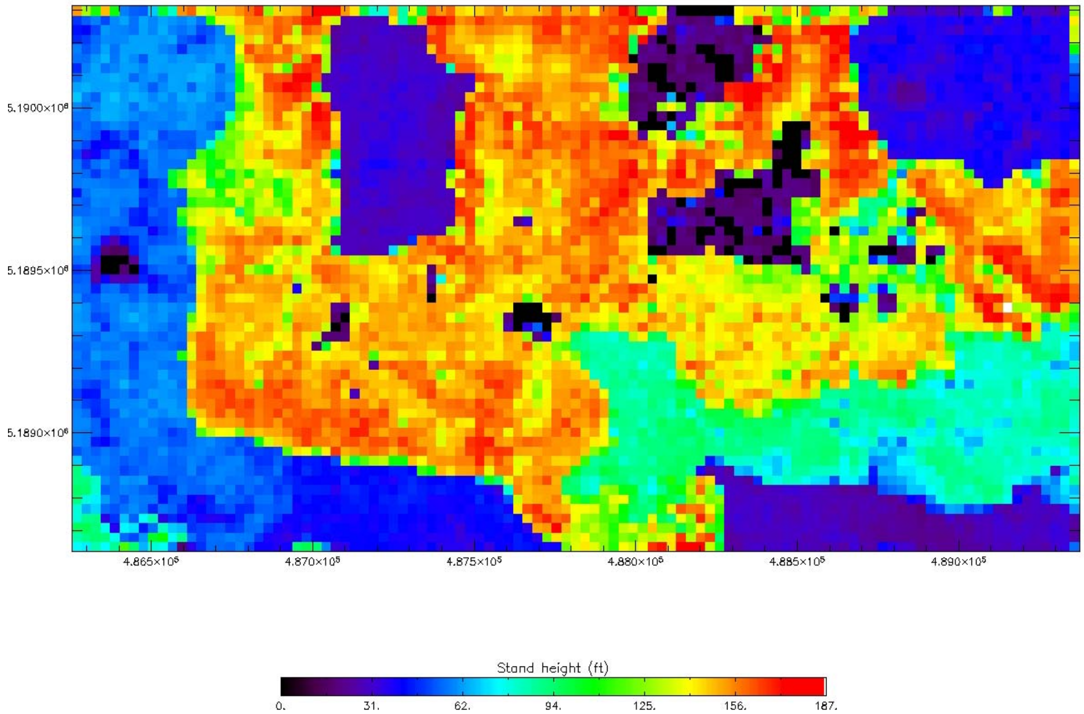

Figure 6. Stand height map (30 meter resolution), Capitol Forest study area

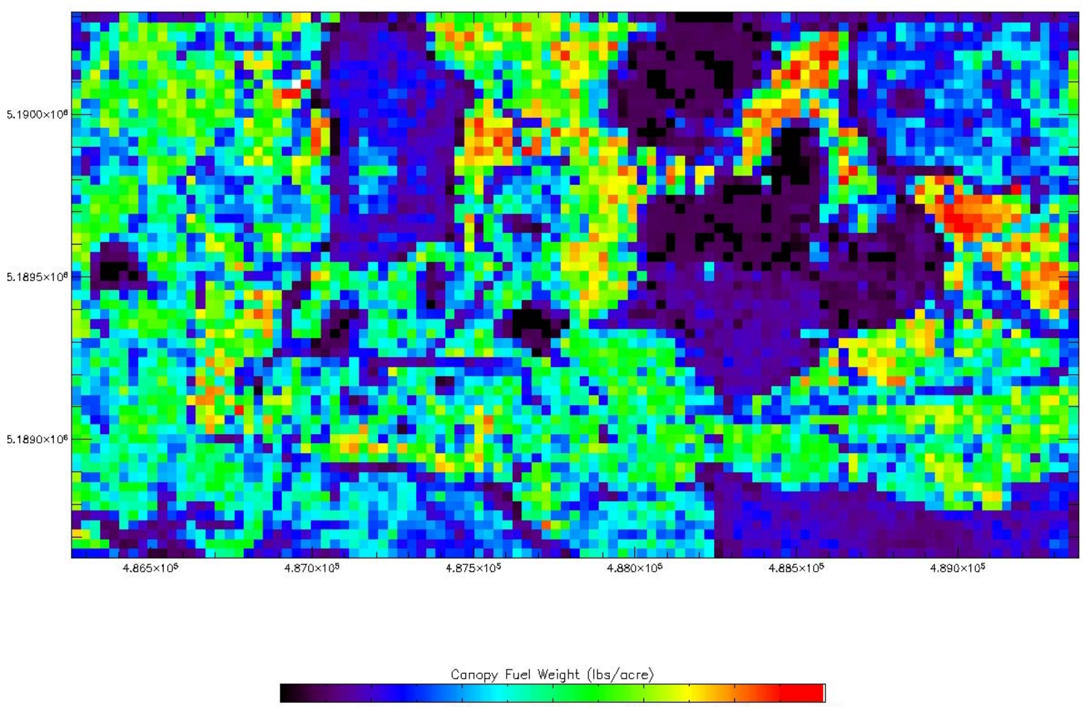

Figure 7. Canopy fuel weight map (30 meter resolution), Capitol Forest study area

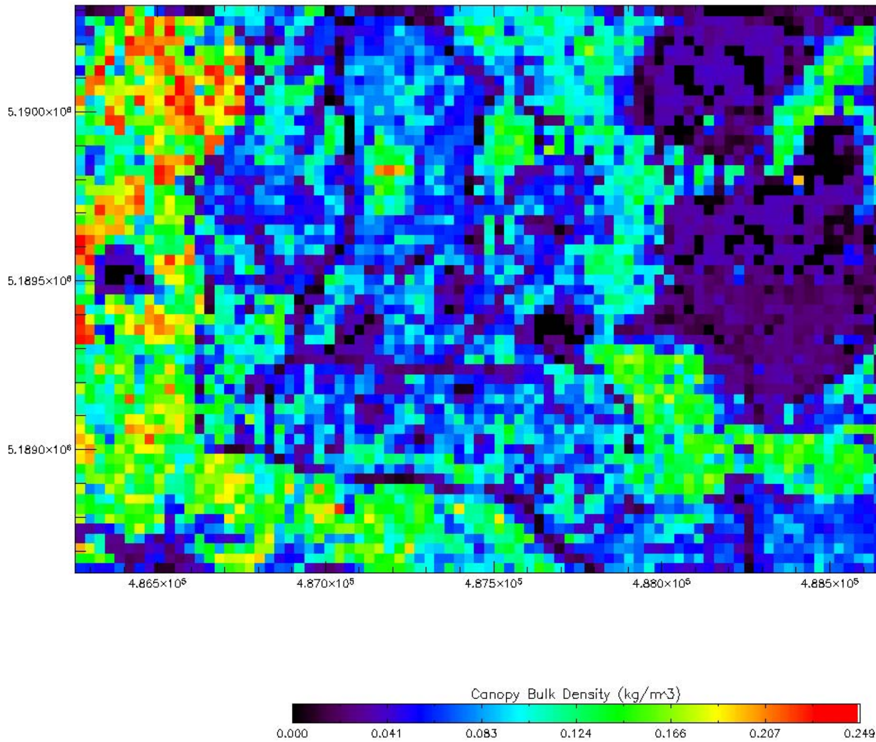

Figure 8. Canopy bulk density map (30 meter resolution), Capitol Forest study area

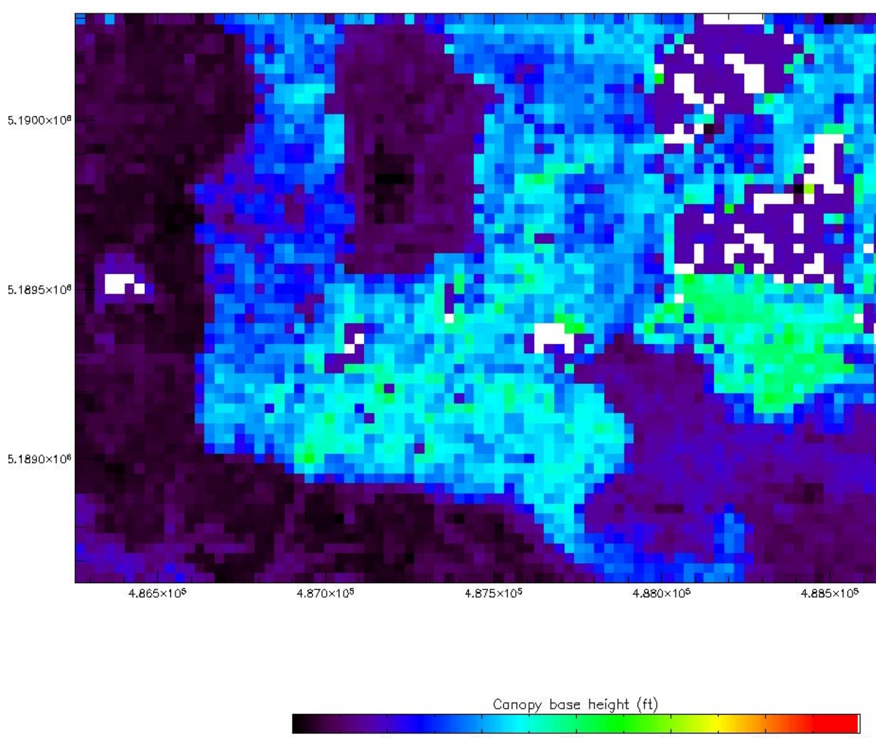

Figure 9. Canopy base height map (30 meter resolution), Capitol Forest study area

DISCUSSION

The results of this study indicate that LIDAR can be used to generate accurate estimates of critical canopy fuel metrics, including total fuel weight, canopy bulk density, canopy base height, and stand height. It appears that the explanatory variables used are capturing structural information related to quantitative canopy fuel characteristics.

There are a number of possible sources for the discrepancy between the LIDAR-based metric within a plot area and the model-based estimate generated from a tree list. First, crown base heights and tree heights for many of the trees were not measured in the field but were generated from regression models. This introduces a significant source of variability into the field-based estimates. Second, defining canopy base height and stand height as a threshold value of crown bulk density makes this metric highly sensitive to the modeling assumptions related to how fuels are vertically distributed. Even small deviations from the assumed uniform distribution of fuels along the length of the crown for several trees in the plot could have a large effect on the estimate of canopy base height and stand height. Edge effects could also lead to significant differences between the LIDAR- and field-based estimates. The tree-list model does not account for the spatial position of tree crowns within the plot, and therefore the crown fuel estimates are calculated for the entire crown associated with each stem falling in the plot, even if a large proportion of the crown is located outside of the plot area. In contrast, the LIDAR data extracted for a given plot includes only measurements of canopy materials that were located within the plot area. Edge effects are likely more pronounced in less dense stands and where plot sizes are smaller.

Another possible reason for a discrepancy between LIDAR and field-based estimates is the nature of laser scanner data. LIDAR data represents measurements of all canopy components, including foliage, branches, and stems. Furthermore, the relative frequency of stem and large branch measurements increases with a lower stem density, since more laser pulses are able to penetrate through canopy openings. However, in the context of canopy fuel mapping, stems and large branches are not considered fuel. This may lead to a negative bias in the LIDAR estimate of canopy base height in less dense stands when compared to the field-based estimates.

When implementing the regression-based approach to modeling crown fuel variables, it is critical to acquire field data over the full range of stand types present in the area to be mapped. Estimates of fuel variables in areas with different stand structures from those sampled are extrapolations outside the domain of the field data and are unreliable. This is particularly evident in the case of estimating crown bulk density (Figure 8) and canopy base height (Figure 10), where the estimates are reasonable within stands where field data was collected, but are very dubious in areas outside of these sampled stand types (i.e. clearcuts, very young stands). It should also be noted that the variability in stand structures present within the Capitol Forest study area is not representative of natural structural variability within Pacific Northwest forests. For example, many of the plots used in this analysis were established in a heavily thinned unit, where many residual trees were taller than 150 feet, yet the fuel loading was quite low due to the low residual stem density (16 trees per acre). The presence of these "unnatural" stand structures in the dataset may have led to the counterintuitive form of several of the regression models (e.g. negative coefficients associated with mean height variables in the estimation of canopy bulk density and canopy fuel weight). Therefore, the regression models developed in this paper are meant to demonstrate the potential of this methodology for crown fuel estimation, and do not necessarily reflect intrinsic structural relationships for natural stands. Although a full model validation was outside the scope of this paper, in an operational context predictive regression models should be validated to assess their applicability over the full range of stand structures present in the area of interest.

CONCLUSIONS

This study demonstrates that LIDAR can be used to estimate canopy fuel metrics efficiently and accurately over large areas. Canopy fuel estimates based upon the LIDAR height data can be used to generate maps that provide a spatially-explicit description of the distribution of canopy fuels over the landscape. These maps (or GIS coverages) can serve as a direct input into a fire-behavior model such as FARSITE, potentially enabling a more realistic and accurate prediction of fire spread and intensity.

In the future, this methodology will be applied to LIDAR collected in different stand types, including a fire-prone site in eastern Washington State. A model validation procedure will be carried out to assess the general applicability of these models in different forest types and with LIDAR data acquired from different systems and at different densities. It is likely that a more extensive pool of explanatory variables will be developed to improve our understanding of the structural relationships between LIDAR height data and canopy fuel characteristics.

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