

Using Airborne Laser Altimetry to Determine Fuel Models for Estimating Fire Behavior

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ABSTRACT

Airborne laser altimetry provides an unprecedented view of the forest floor in timber fuel types and is a promising new tool for fuels assessments. It can be used to resolve two fuel models under closed canopies and may be effective for estimating coarse woody debris loads. A simple metric—obstacle density—provides the necessary quantification of fuel bed roughness to make these measures possible. This work highlights the need for more research in the application of laser technology to fuels mapping.

Keywords: mapping; remote sensing

Accurate, spatially explicit fuels data are increasingly needed as land management agencies embrace prescribed fire and thinning as viable fuels-reduction alternatives. These data would be used to create and implement fire policy at the local, regional, and national levels and to drive the computer models that allow prediction of fire behavior, smoke emissions, and fire effects.

Four recent developments highlight the need for comprehensive fuels mapping:

1. Fire is now recognized as an essential natural process in many ecosystems, and land managers are beginning to use landscape-level fuels treatments to improve ecosystem health and to reduce the likelihood of catastrophic fires.

2. An expanding urban interface and an increasingly litigious society have narrowed the margin for error in fire management decisions.

3. Fire managers are now required to use complex, data-intensive fire-behavior and smoke-production models to support environmental assessments and burn plans.

4. Fire managers must provide more explicit fire-behavior predictions for real-time support of suppression tactics and logistics decisions.

Remote sensing is an important tool for fuels inventory because it can be used to provide consistent and relatively inexpensive data for large land areas. From a fuels mapping standpoint, however, traditional remote sensing is limited by the inability of optical sensors to collect information from beneath tree canopies (Keane et al. 1998). A new generation of active sensors—airborne laser ranging systems—may provide the forest floor measurements needed for accurately mapping fuels, although they have not yet been shown capable of doing so. This study explores the potential of air-

borne laser altimetry for identifying fuel models in closed-canopy Western conifer forests.

Laser altimetry uses light emissions to measure ranges between itself and a reflective surface. An airborne instrument emits pulses of electromagnetic radiation toward the Earth and collects the backscatter using nanosecond-resolution clocks to time the roundtrip propagation of each pulse (Bufton 1989). The speed of light is used to calculate the distance from the sensor to the target, while integrated global positioning and inertial navigation systems provide precise geolocation for each pulse. Earth surface structural parameters such as slope and vegetation height are determined by analyzing the location, intensity, and temporal distribution of backscatter radiation collected from groups of reflections.

Laser altimetry is not a new technology, having been used for almost three decades in the space sciences to map topographic surfaces of planets and moons. However, only in the past 15 years have researchers turned toward the Earth's surface with the goal of measuring vegetation attributes. Today, advances in affordable lasers, geolocation, and clock technology have spurred commercialization of laser altimetry, making it more accessible for general forestry applications. At least 40 firms provide laser altimetry services

Plot 216. Fuel Model 8, total fuel load 5.8 tons per acre.



Plot 187. Fuel Model 10, total fuel load 35.8 tons per acre.



Photos courtesy of USDA-FS Fire Sciences Laboratory

Figure 1. Representative fuel types of the Tenderfoot Creek Experimental Forest, Montana.

worldwide (Baltasvias 1999), and the industry is beginning to move from a developmental stage into a service stage.

Laser altimetry has been shown capable of providing relatively precise measurements of canopy height, canopy cover, vertical canopy distribution, surface roughness, and ground surface topographic elevation (Nelson et al. 1988a; Ritchie et al. 1992; Weltz et al. 1994; Magnussen and Boudewyn 1998; Pachepski and Ritchie 1998; Naesset and Bjercknes 2001). In addition, reasonable estimates of forest biomass, volume, and basal area are possible (Nelson et al. 1988b; Nilsson 1996; Naesset, 1997; Nelson et al. 1997). To date, no one has explored the ability of this technology to measure roughness of the forest floor beneath closed canopies, although van der Veen et al. (1998) demonstrated that reasonable surface micro-roughness measurements are obtainable. Given the obvious need for reliable fuels data from the fire and forestry communities, this compelling application is explored further here.

Approach

To predict fire behavior and to a lesser extent to estimate fire effects, fire managers use the 13 standard fuel models of Albin (1976) along with wind, slope, and moisture data. The fuel models are general representations

of fuel beds that have specific, difficult-to-measure fuels properties (i.e., fuel load by size class, packing ratio, and surface area to volume ratio). The strength of these models is that they allow a forester to obtain the fuels attributes necessary for predicting fire behavior by matching images and descriptions with the fuel bed at hand rather than actually measuring each attribute. Fire managers can use experience of past fire behavior with photo guides like Anderson's (1982) to invoke the appropriate fuel models that will describe the fire behavior in a specific fuels landscape.

In the closed-canopy conifer forests of the western United States, the two most frequently invoked fire behavior fuel models are model 8 (closed-canopy short-needle conifers with light fuel loads and little undergrowth) and model 10 (closed-canopy conifers with heavy dead/down fuel loads and significant regeneration) (*fig. 1*). Distinction between these models is important because fires in fuel model 10 will burn at the upper limit of control by direct attack, whereas fires in model 8 are typified by slow-moving surface fires with short flame lengths. In the field, these models are usually easy to distinguish from one another, but from the air they often appear identical. Consequently, land managers have not been able to map hazard fuels effectively from air

photos or digital images across the vast expanses of forest that characterize the western United States.

For the purpose of the exploratory work presented here, the Tenderfoot Creek Experimental Forest was chosen as a study site, primarily because it spanned the range of fuel conditions within fuel models 8 and 10. The Tenderfoot Forest is a 9,125-acre research area on the Lewis and Clark National Forest in west-central Montana and is characterized by lodgepole pine and spruce/fir stands spanning a successional pathway from young, even-aged stands of lodgepole to multistoried, senescent mixed conifer with significant regenerative understory.

Laser altimetry data were obtained for two watersheds in the Tenderfoot Forest with an Aeroscan lidar system contracted through Spencer Gross Engineering, Inc. The system was flown aboard a Piper Navajo Chieftain aircraft at 9,000 feet above mean terrain. It uses a pulsed laser that scans across the track of the flightline, resulting in an irregular grid of data points on the ground. At least one return is recorded from each pulse, but the unit is able to record up to five returns per pulse if enough energy is reflected from various parts of the canopy and ground to trip the receiver that many times. The size of each laser footprint and the density of footprints can be adjusted by chang-

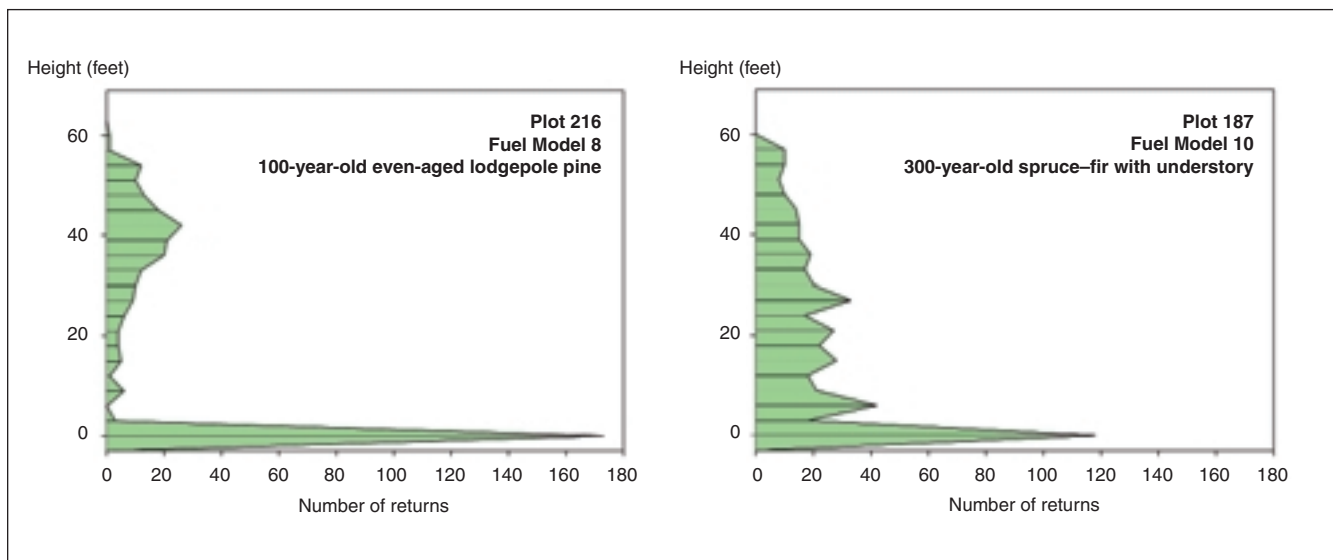


Figure 2. Laser height profiles for two 0.10-acre plots representative of fuel models 8 and 10, respectively. These are the same plots depicted in figure 1.

ing the flying height of the aircraft, its airspeed, the laser pulse rate, scan rate, and scan field of view. For this study, these parameters were adjusted so that the nominal footprint size was 2.95 feet and the average return density was one per 8 square feet.

Laser data were extracted for 33 0.10-acre circular fixed-area plots on which fuels attributes had been measured. Fuel load was assessed on each plot by time-lag size class after Brown et al. (1982) following ECODATA collection protocols (Keane et al. 1990), and the height, crown, and diameter at breast height (dbh) of all trees were measured. Leaf, branch, and stem biomass in the fuel bed were calculated from these measurements using equations proposed by Moeur (1981) and Ter-Mikaelian and Korzukhin (1997). Fuel models were assigned by experienced fire personnel using Anderson's (1982) guide.

Canopy laser hits were separated from ground returns manually, and a median ground surface was created from the ground measurements. The height of each return above this median ground surface was calculated, and all points potentially within the fuel bed (≤ 6 feet in height) were extracted. Obstacle density, a surface roughness metric from the aerodynamic roughness literature (de Vries 1999), was calculated from these points. Obstacle density is defined as the number of nonground points

within the fuel bed per square meter, normalized by the total number of ground and fuel returns.

Results and Discussion

Profiles of laser returns as a function of height above the estimated median ground surface demonstrate the characteristic distributions of material in the vertical domain for fuel models 8 and 10 (fig. 2). Visual comparison of these height profiles with the photographs in figure 1 show that the laser data roughly depict a unimodal distribution of biomass in fuel model 8 and a multimodal distribution in model 10. Further, a significant fraction of the returns in fuel model 10 come from within the fuel bed, whereas few occur in the fuel bed of model 8. This comparison supports our intuition that fuel beds in model 10 should have rough reflective surfaces relative to those in model 8, and that a metric like obstacle density might characterize this difference.

At the Tenderfoot site, laser-derived obstacle densities (OD) less than 0.082 describe plots characterized by fuel model 8, where total dead plus live fuel load is less than 16 tons per acre (fig. 3). On plots with obstacle densities greater than 0.082, fuel model 10 is characteristic, with fuel loads exceeding 16 tons per acre. An analysis of variance (ANOVA) shows that between-fuel model OD variance greatly exceeds within-group variance (F ratio:

45.591) and that the two samples of fuel models have been drawn from different populations ($\text{Prob} > F: 0.000$). If we accept the validity of this obstacle density threshold, and for the moment ignore fuel models 1 and 2, then fuel models 8 and 10 can be distinguished correctly in 28 of 31 cases (90 percent). More specifically, if the landscape was comprised only of fuel models 8 and 10, 89 percent of the time we could correctly identify fuel model 8 and 92 percent of the time we could correctly identify fuel model 10 (producer's accuracy). The probability that an obstacle density below 0.082 is fuel model 8 is 0.94, and the probability that an obstacle density above it is fuel model 10 is 0.85 (user's accuracy).

In the three cases where the obstacle density threshold of 0.082 did not correctly separate model 8 from model 10, it is not certain that the laser altimetry estimate is wrong and the field estimate is correct. On postanalysis field inspection of the plots, we suggest that the laser-derived estimates of fuel models are more consistent than field estimates, and that the laser data correctly identified the appropriate timber fuel models in all 31 cases. This observation highlights one of the potential problems with field mapping fuel models—that fuel model classification is largely subjective with each model incorporating a range of fuels attributes.

A plot of total dead versus live fuel for the Tenderfoot data reveals some of

this subjectivity (*fig. 4, p. 14*). Dead fuel load is clearly the primary observation by which field personnel distinguish fuel model 8 from 10, and it is interesting to note the consistency with which field personnel classified the fuel models along the dead fuel gradient. There is no such consistency along the live-fuel-load gradient, suggesting that live fuels were not a factor in assignment of fuel models. As a result, six of the plots classified as fuel model 8 by field personnel contain a significant fraction of live, combustible biomass but relatively little dead fuel, and therefore probably do not belong in either fuel model 8 or 10. Rather, they represent fuel conditions where rates of spread and fireline intensities would be characteristically low except during dry windy periods, where torching and crowning is likely. Fuel beds like these raise one of the thorny issues in fuels mapping, i.e., where does one establish breakpoints between the timber fuel models? In reality, these breakpoints are dynamic and change as a function of weather conditions. What we would really like to know, then, is which fuel model 8s might burn like 10s under the right conditions, and which fuel model 10s might burn like one of the slash fuel models under these same conditions.

The obvious linear relationship between obstacle density and total fuel load observed in *figure 3* does suggest that laser altimetry could be used to estimate coarse woody loads directly, thereby resolving some of the breakpoint issues discussed above. Herein lies one of the more promising features of laser altimetry—the potential to estimate fuels across a continuum rather than placing fuels into discrete classes. Recall that a fuel model is essentially a distillation of fuels attributes that govern fireline intensity and rates of spread, i.e., fuels less than 3 inches in diameter. From this work, it appears that laser altimetry is more effective for estimating the larger fuels that contribute to crowning, spotting, and a variety of fire effects that occur after passage of the flaming front rather than for the fine fuels that govern rates of spread. Although laser altimetry is very effective for assigning fuel models to

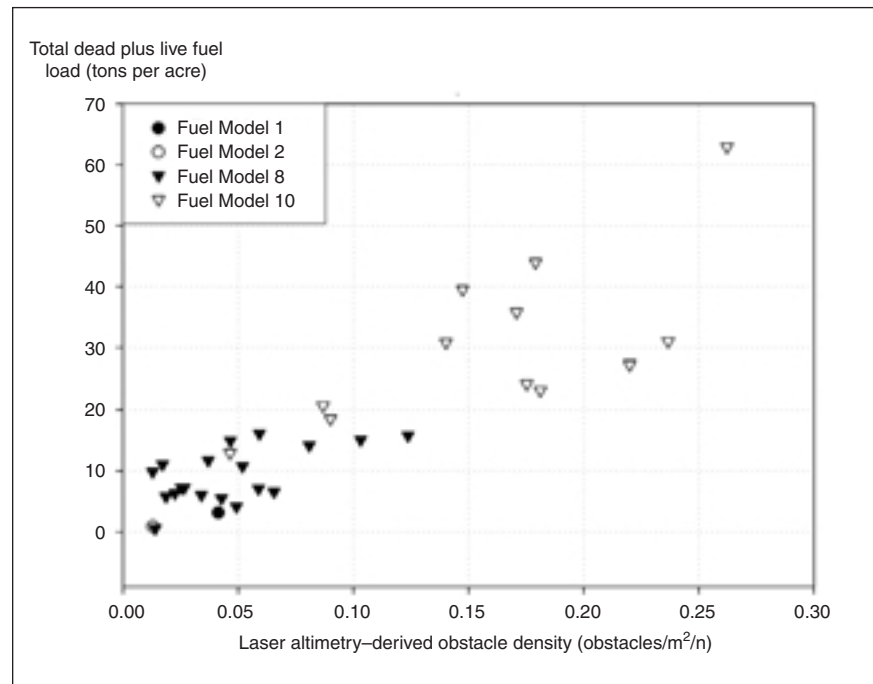


Figure 3. Obstacle density versus total fuel load shows that fuel models with relatively light fuel loads appear smooth (low obstacle densities) compared with fuel models characterized by heavier coarse woody debris loads. Further, fuel model 8 can be distinguished from fuel model 10 at an obstacle density of roughly 0.082.

timbered landscapes with closed canopies, this is probably an underutilization of the data. Clearly, more research is needed in this area.

If laser altimetry-derived roughness is primarily a function of coarse woody debris in the fuel bed, as it appears to be, then considerable attention must be directed toward understanding the complex and differential interactions between incident laser radiation and fuel bed components. In the context of live versus dead fuel discussed above, it appears that large logs and branches in the fuel bed dominate the roughness signal even on plots with significant shrub and seedling-sapling components. Therefore, we might tentatively hypothesize that leaf, stem, and branch biomass of small trees and shrubs do not present good reflective surfaces to the laser altimeter relative to large, horizontally oriented logs and branches (i.e., dead coarse woody debris).

To this point, our discussion has been limited to timber fuel models 8 and 10, in part because these are two of the most difficult to resolve using remote sensing. Of course, the landscape is not composed only of these two fuel models, and the data utilized in this

study contain one plot each of fuel models 1 (Western annual grasses) and 2 (open pine with an annual grass understory). Although too few in number to ascribe significance, these data highlight several additional considerations. First, both plots have relatively smooth fuel beds and correspondingly low obstacle densities, and consequently overlap with the OD distribution of fuel model 8. The laser altimetry data cannot provide differentiation between short-needle conifer litter and short annual grasses given the similarity of their reflective surfaces, and in fact our data clearly show that obstacle density is primarily a function of coarse woody debris loads (pieces > 3 inches in diameter) which dominate the total fuel loads depicted in *figure 3*. Fuel models 1 and 2, then, might best be distinguished from model 8 by evaluating the distribution of laser hits within the canopy in addition to those analyzed in this study. Several researchers have demonstrated the efficacy of laser altimetry for estimating forest volume, biomass, basal area and stem density (Nelson et al. 1997; Naesset and Bjercknes 2001), lending credibility to the idea that a fuel model 8, which is char-

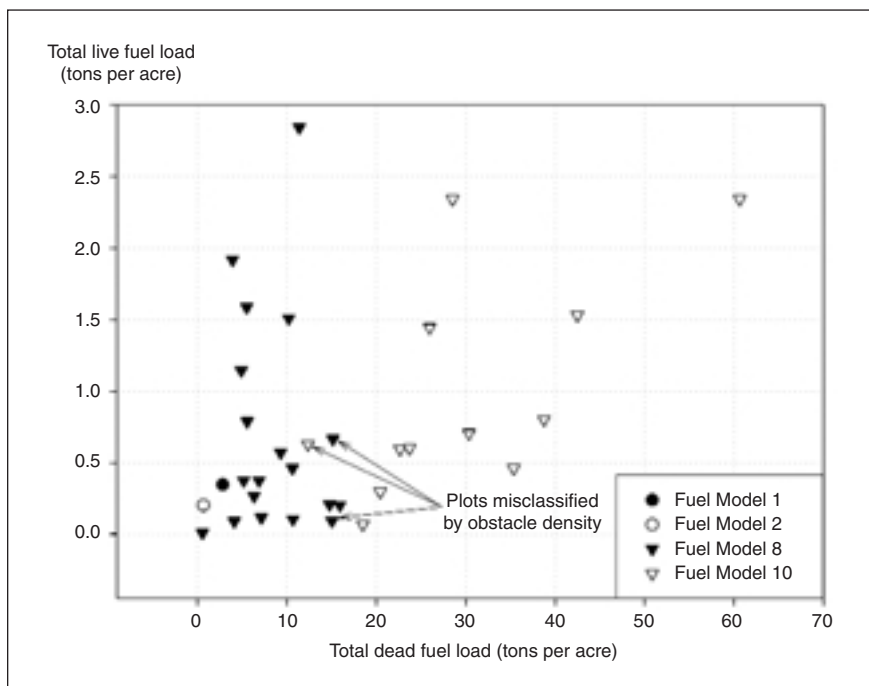


Figure 4. Total live versus dead fuel load reveals that field fuel model classification is largely based on dead fuels. The breakpoint between these fuel models is between 13 and 16 tons per acre of dead woody debris.

acteristically closed-canopied, could be separated from models 1 and 2, which have open canopies or an absence of trees.

Finally, one timber fuel model not represented in the Tenderfoot data, but important to fire behavior, is fuel model 9 (closed-canopy long-needle pine litter). Model 9 should look much like model 8 in terms of obstacle density, but fire behavior is significantly different, as model 9 exhibits consistently higher rates of spread under similar meteorological conditions. To distinguish fuel model 9 from model 8, therefore, information in addition to the laser altimetry data will be necessary to distinguish short-needle conifer stands from long-needle stands. This information might come in the form of biophysical-setting data or land-cover maps, which draws attention to the considerable potential of active-passive remote sensing data fusion. Again, more research is needed in this area.

Conclusions

Traditional optical remote sensing techniques have been used with some success to generate fuel model maps with accuracies approaching 60 percent (Keane et. al. 1998). Much of the

error in these maps is attributable to the timber fuel types, which are difficult to identify because the canopy obscures surface fuels. Further, they rely on not-widely-available ancillary data and considerable subjective human input, resulting in a product that (1) is difficult to tile with adjacent fuel maps because the methods and data used to create it are diverse and often unique, (2) is generally only useful for fire behavior prediction and not for any other purpose, and (3) quantifies fire behavior classes rather than direct measures of fuels.

Many in the remote sensing community have long thought that these problems might only be overcome by using active remote sensing techniques such as laser altimetry. However, it is only recently that we have been able to explore the efficacy of this technology for fuel mapping. The research presented here confirms that laser altimetry can provide unprecedented resolving power for discrimination of fuel models 8 and 10 in closed canopies at Tenderfoot Creek Experimental Forest and may allow direct estimates of coarse woody debris loads. These results are remarkable given the array of confounding factors that could mask

the relationships between surface roughness and fuels attributes, and are promising enough to merit further exploration of laser altimetry for fuels mapping.

The work presented herein is admittedly confined to a small geographic area and to a select few fuel models. Additionally, the obstacle density metric is but one of many that could be used to characterize surface roughness in a fuels context. However, this work is a starting point for research that could lead to effective fuels mapping across large areas. As costs continue to fall and as new software is developed that allows people to work more easily with laser data, we anticipate that laser altimetry will become a tool of choice for fuels mapping applications.

Future research will certainly involve establishing the relationships between roughness and actual fuel loads that our data seem to suggest. Fuels mapping will then need to be carried out on large, continuous landscapes and in a more diverse assemblage of fuel types. Along the way, new methods for canopy-ground separation will be needed, additional roughness metrics should be investigated, and data acquisition parameters explored. Issues of cost, scale, and reproducibility are implicit in each of these areas. Finally, the potential ability of laser altimetry to provide canopy attributes that are important for predicting initiation and sustenance of destructive crown fires (e.g., crown bulk density and vertical continuity of biomass) is significant and certainly requires further investigation. Researchers should explore fusion of traditional optical remote sensing methods with laser data, and we believe these methods will lead to an unprecedented ability to characterize the distribution of forest fuels in both the horizontal and vertical domains.

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