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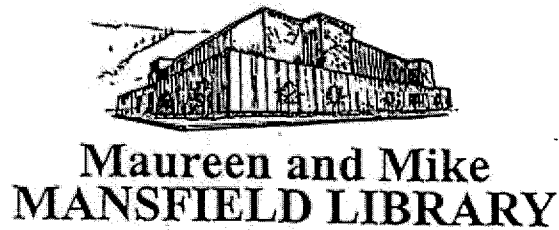
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USING LIDAR REMOTE SENSING TO ESTIMATE FOREST FUELS

by

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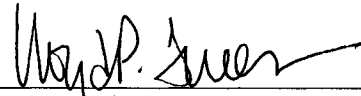
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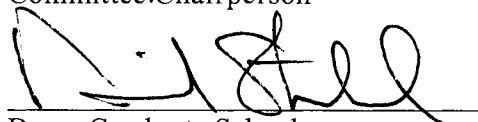
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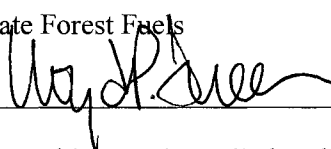
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Using Lidar Remote Sensing to Estimate Forest Fuels

Director: Dr. Lloyd P. Queen



An emerging technology, airborne laser altimetry, is applied to the problem of remotely sensing surface fuel characteristics beneath closed-canopies of lodgepole pine (*Pinus contorta* Dougl. ex Loud.) in west-central Montana, U.S.A. Its ability to provide effective discrimination of FPBS (fire behavior prediction system) fuel models and accurate estimates of coarse woody debris is successfully validated using plot data with coincident field and laser altimetry-based estimates of fuel bed parameters. The surface roughness metrics of obstacle density, standard deviation of the ground-height distribution (GHD), and kurtosis of the GHD correlate highly with field estimates of fuel volume/load/surface area. These relationships can be exploited to predict fuel attributes at the plot-level ($r^2 \sim 0.8$). The observed relationships are driven by coarse woody debris in the fuel bed, and not by live biomass or smaller dead fuels. Further, it appears that surface roughness does not depict discrete fuel entities, but rather that woody debris causes scattering of incident laser radiation such that the apparent ground surface of heavily loaded plots is highly variable relative to those with less fuel accumulation. Comparison of a laser-derived continuous 1000-hr fuel surface (> 3 -inch diameter pieces) with both plot-level and area-based field estimates demonstrates that plot-level relationships are scalable to the landscape, and that laser altimetry is useful for characterizing both the distribution of fuel accumulations and their within- and between-patch variability. However, it appears unable to assist in discrimination of rough surfaces caused by the presence of coarse woody debris and those caused by geomorphic roughness. The 1000-hr fuel surface is spatially consistent with independently-derived photomorphologic units from high spatial resolution optical imagery and with fire history. Specifically, regions characterized by heavy fuel accumulations correspond with texturally rough canopies and the occurrence of single fires that burned at least 250 years ago. In regions with lighter fuel loads and more complex fire histories, these relationships break down, lending credibility to the idea that laser altimetry-derived fuel maps may be helpful for documenting fire history in mixed-severity regimes characterized by episodes of frequent fire activity. The technology is clearly valuable for mapping surface fuels in heavily forested areas and is capable of filling the gap between the needs of fire behavior analysts and fire ecologists by providing useful estimates of the coarse woody debris that affect smoke production, duff consumption, soil exposure, and heat transfer to the soil. However, although its ability to provide consistent, fine-grained fuels data across broad geographic areas is evident, it must be evaluated in the context of the significant cost, time, and energy associated with collecting such data, thus reemphasizing the importance of carefully evaluating one's data needs.

Acknowledgements

Admittedly, serendipity has played a large role in my experiences at the University of Montana, and I consider myself fortunate to have worked with many of the past and present inhabitants of our small corner of the Science Complex. My advisor, LLOYD Queen, deserves special thanks because he created the great working environment and populated it with talented, hard-working people. His confidence in the people that work for him is a tremendous asset. Of course, I would not have made it this far without the continuous comedy that is the Pixel Ranch. Special recognition goes to the original crew of Jim Riddering and the late Brad Villnow. There are just a few people whom can be counted on in any situation and these are two of them. Thanks to Don Helmbrecht and the rest of the ranchers who provided technical expertise, humor, entertainment, and support, and to Ken Brewer, who despite hitting the wall, deserves mention for his insights, friendship, and willingness to help. Peter Thornton, Mike White, and Matt Jolly, of NTSG fame, set a high bar and continue to inspire, and Saxon Holbrook, who usually gets mentioned for his technical expertise, has been even more important as a friend and hunting partner. Steve Running deserves the credit for recognizing the talents of these people, and is thanked along with Ron Wakimoto, Hayley Hesseln, Elizabeth Reinhardt, and Bob Keane for serving on my committee. Youngee Cho and Cate Crue also deserve special recognition for tireless support of the oddball cast of characters that make up NTSG and the Fire Center. A number of other people and organizations require acknowledgement. The Missoula Fire Lab was instrumental in initiating and supporting this project. Specifically, Colin Hardy, Duncan Lutes, Helen Smith, and Kirsten Schmidt shared considerable data, time, and expertise. Leon Theroux and Ward McCaughey of the Missoula Forest Sciences Lab gave insight into, and access to the Tenderfoot. I owe a great deal to my mom and dad, George and Dolores, and to my sister Andrea and brother Mark, who by example, have always inspired me to try to be a good person. Finally, and most importantly, thank you Cathy, my lovely wife, who gave birth to our first child, Jim, right in the middle of this whole mess, and performed the heroic duties necessary to keep all of us healthy and happy throughout it.

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CHAPTER 1

INTRODUCTION- FUELS AND REMOTE SENSING

Overview

The goal of this dissertation research is to assess the ability of airborne laser altimetry to estimate and to map surface fuels accurately in forested landscapes. In the absence of a significant body of relevant literature, the work is exploratory, focusing on remotely sensing surface fuels beneath closed-canopied lodgepole pine (*Pinus contorta* Dougl. ex Loud.). It is organized into four chapters, ordered chronologically to match the exploratory progression of the work. Although independent, each chapter necessarily builds upon its predecessors and incorporates a common fire management applications perspective. Chapter one provides context, background, and a statement of objectives. In chapter two, laser altimetry-based surface roughness is used to derive Fire Behavior Prediction System (FBPS) fuel models in timbered landscapes. This work will appear in the June 2003 issue of *Journal of Forestry*, introducing the application to a broad cross-section of foresters. In chapter three, the relationships between surface roughness and fuel attributes are quantified with the goal of estimating surface fuels directly with laser altimetry data. This research is in review by the *Canadian Journal of Forest Research*. Chapter four describes a mapping exercise in which a continuous fuels surface is generated, validated, and placed in the context of fire history. It will form the basis for an article in a journal specializing in fire science.

Statement of problem

Fuels are currently a topic of great interest in the land management community, in large part because of an ongoing fifteen-year-long period of unusually severe fire seasons (National Fire Plan, 2003). National attention has rather suddenly focused on the perceived consequences of 70 years of fire suppression, leading to considerable discussion of management strategies aimed at reducing hazardous fuel accumulations and restoring fire to fire-dependent ecosystems. Four of the Fire Plan's five key elements (firefighting, rehabilitation/restoration, hazardous fuel reduction, community assistance) contain fuels as a dominant theme, and fuel management has become a core objective of a variety of policy-making and research organizations (Western Governor's Association, 2002; Joint Fire Sciences Plan, 2003).

In theory, fuel management presupposes that we know something about the type, quantity, and distribution of the fuels to be managed. However, in practice this is not often the case, particularly in the realm of fuel distributions. A review of the literature suggests that the state of knowledge in fuels science has not changed significantly since the early work of van Wagner (1968), Brown (1970, 1982), Brown et al. (1974), and Albini (1976). We still define fuels primarily to meet the requirements of the National Fire Danger Rating System (Deeming and Brown, 1975; Deeming et al., 1977) and fire behavior prediction models (Rothermel, 1972; Albini, 1976), and we measure fuels in the field with methods developed 25 years ago. Although these applications and measurements are not necessarily inconsistent with current fuel management objectives, they do not explicitly incorporate the spatial elements necessary for characterizing fuels across large landscapes.

The spatially explicit fire behavior model FARSITE (Finney, 1998) codified the need for spatially-continuous fuel surfaces with its attendant requirement for gridded data. This need still poses significant limitations on the model's use, and has driven development of fuels mapping methodologies that incorporate remote sensing data (Keane et al. 1998). Remote sensing is a

logical tool for such work because it can efficiently provide data sets for large land areas. Images are usually digital, cost-effective, have consistent geometric fidelity, and are widely available to users (Wynne and Carter, 1997). However, although most land management agencies currently use some form of remote sensing for resource inventory, from a fuels standpoint they have been limited by the fundamental inability of existing sensors to characterize the forest floor beneath tree canopies. The work of Jakubauskas (1996) highlights some of the difficulties associated with generation of fuels data from relatively high-spatial-resolution optical imagery like Landsat Thematic Mapper. He showed that the spectral characteristics of lodgepole pine allowed effective discrimination of two general classes: post fire regeneration (0-40 yrs old) and mature forest (40-350 years old). Little within-class discrimination was possible, particularly in older stands. Field spectral analysis showed that age-dependent differences in reflectivity of forests were attributable to the relative contributions of overstory, shadow, and understory. As stands approached 40 years in age, overstory and shadow increasingly dominated the spectral response, and understory disappeared from it entirely at 40 years.

Other remote sensing research has looked more specifically at the understory's contribution to forest spectral response. Stenback and Congalton (1990) showed that Landsat TM imagery could be used to identify the presence or absence of understory beneath sparse to moderately-dense deciduous canopies with a producer's accuracy of 55-66 percent. Ghitter et al. (1995) correctly detected white spruce regeneration under boreal deciduous forest using leaf-on/leaf-off TM imagery in 74 percent of cases. Neither of these studies identified what comprised the understory, only whether there was an understory or not. Further, they chose simple environments (open deciduous canopies with evergreen understory) to test the hypothesis that understory could be discriminated spectrally.

The conclusion is that optical remote sensing is fundamentally limited as a tool for measuring most of the fuels characteristics important for fire behavior and fire effects

applications in forested landscapes. This is because surface fuels do not usually contribute to reflectance in these environments, and because the links between fuels and the parts of the forest that do contribute to reflectance are generally unpredictable. Although discrimination between some forest stands is possible (Jakubauskas, 1996; St-Onge and Cavayas, 1997), many of the fuels attributes within these stands cannot be assessed directly. Further, it is doubtful whether distributions of surface fuels consistently match the distribution of stands. The approach to using traditional remote sensing techniques for fuels inventory, then, has been to link spectral characteristics of the terrestrial surface with fuels attributes that may not be directly related to them. This link is forged through integration of ancillary data sets like biophysical settings and forest inventories (Keane et al., 1998), resulting in reasonable approximations of at least one specific surface fuel attribute (FBPS fuel model).

For the reasons discussed above, it is believed that incremental advances in fuels mapping will continue to occur as optical remote sensing and modeling techniques are refined, but major progress will be possible only through development and implementation of new forms of active remote sensing like light detection and ranging (lidar). This belief forms the impetus for the work presented here.

Active remote sensing techniques have long held promise as means of assessing the vertical dimension of the earth's surface. They differ from other techniques in that electromagnetic radiation with known properties is emitted and the backscatter collected, usually by the same device. The two most common types of airborne/spaceborne active remote sensing are lidar and radar. At a most general level, footprint size distinguishes one from the other, where footprint size is wavelength dependent. Lidar is characterized by 1 to 50 meter spatial resolution from a single pulse while a radar footprint can be measured in degrees. Lidars produce narrower beams of radiation than radars ($\sim 1\mu\text{m}_\lambda$ versus $>2\text{cm}_\lambda$) by operating at shorter wavelengths and higher intensities (where $\text{beamwidth} = f(\text{pulselength, wavefront curvature})$) (Bufton, 1989). Short

wavelengths require shorter receiver focal-lengths and a consequently smaller angular field of view (AFOV) because AFOV is roughly equivalent to wavelength divided by focal length. Each lidar pulse, then, provides a unique measurement of the earth's surface while radar requires averaging of many pulses. Consequently, lidars can be used to measure the microroughness of the earth's surface, a variable that creates noise in radar data (Krabill et al., 1995; van der Veen et al., 1998; de Vries, 1999).

The ability of lidar to characterize micro-roughness at scales consistent with fuel distributions (Krabill et al., 1995), suggests that the technology might be useful for assessing fuel bed attributes. However, it is not clear whether estimates of micro-roughness are obtainable beneath tree canopies. The resolution of this issue and the subsequent examination of relationships between roughness and surface fuel bed attributes are the focus of this dissertation. The primary goals of the work are: (1) to determine the capacity of laser altimetry to quantify surface fuels and, (2) to apply the results of (1) to demonstrate the utility of the technology for their spatial characterization.

In order to achieve these goals, it becomes necessary to identify characteristics of the fuel bed to be examined. I start with what is perceived as the simplest characteristic, FBPS fuel model, because it integrates many elements of the fuel bed that might be depicted by surface roughness estimates (Chapter 2). Following, the specific fuel bed attributes of load, volume, and surface area are addressed for fuels of different size classes, and regeneration (live coniferous biomass) is evaluated (Chapter 3). Finally, a single attribute is selected with the strongest link to surface roughness, it is mapped, and its distribution evaluated in the context of fire dynamics (Chapter 4).

Given the exploratory nature of the work, the discussion of which fuel attributes are the most important, at what spatial scales should they be mapped, to what accuracy, and at what cost, are postponed. The answers to these questions are vexing, and will differ depending on the

reasons for measuring fuels in the first place. Certainly, fire behavior analysts, ecologists, and planners have diverse needs for fuels data and different requirements for attributes, scale, accuracy, precision, and cost. The research presented here does not attempt to reconcile these differences directly, but rather, attempts to identify some of the attributes that are quantifiable with laser altimetry at as fine a grain as possible. It would be premature to do otherwise, given the current state of knowledge of application of the technology to fuel mapping.

State of knowledge

Lidar remote sensing of vegetation is in relative infancy as a technology and still requires basic exploratory research to identify its abilities and limitations. However, there is a body of literature, albeit small, suggesting that laser altimetry might be useful for assessing fuels. For example, several authors have shown that surface micro-roughness is obtainable with laser altimetry on bare-ground surfaces like water, beaches and icefields (Krabill et al., 1984; Bufton et al., 1991; Krabill et al., 1995; Vaughn et al., 1996; van der Veen et al., 1998). Surface features can be mapped with an accuracy of 10-15 cm over flightlines several hundred kilometers long (Krabill et al., 1995). These bare-ground applications utilize lidar as it was originally intended (to map the topographic surfaces of planets and moons), and they show that fine-grained roughness estimates that might be necessary to depict surface fuels are achievable in non-vegetated environments. On vegetated landscapes, however, the ground surface must be carefully separated from laser hits within the vegetation canopy (Kraus and Pfeifer, 1998; Lohr, 1998; Petzold et al., 1999), a potentially troubling issue to those interested in topographic ground surfaces, and by association, to those interested in fuel beds.

Ironically, the data that were originally discarded (the vegetation 'noise') now form the basis for a number of studies aimed at measuring vegetation characteristics. Laser altimetry has

been used experimentally to estimate biomass, stand volume, canopy height, and canopy cover (Nelson et al., 1988a; Nelson et al., 1988b; Ritchie et al., 1992; Weltz et al., 1994; Nilsson, 1996; Naesset, 1997a; Nelson et al., 1997; Magnussen and Boudewyn, 1998; Naesset, 1999; Harding et al., 2001; Naesset and Bjerknes, 2001; Drake and et al., 2002). These researchers collected lidar data in regions with known structural characteristics and then regressed ground estimates of structural metrics against laser measurements.

Initially, this approach proved problematic because it depended upon accurately locating narrow laser transects on the ground. Horizontal georeferencing of small footprint data was extremely difficult even with many ground control features (e.g., Nelson et al., 1988a; Curran, 1988), although this problem has largely been overcome with development of more effective Global Positioning System (GPS), clock, and inertial measurement unit (IMU) technology. Further, the narrow ground tracks often did not provide a representative profile of forest structure (Nelson et al., 1997). For example, in some cases ground plots were overlapped by adjacent, taller overstory trees causing systematic overestimation of canopy height.

An alternative to the laser-field regression approach has been to model relationships between forest structure and laser data using digital stand data. Nelson (1997) and Nelson et al. (1997) simulated laser transects across two-dimensional, digitized stands of Costa Rican tropical forest to develop regression equations for basal area and stand volume estimates. They then used these equations with a lidar dataset to calculate basal area and stand volume to within 23% of ground-based measurements for a single 50m transect. On two additional transects, basal area and stand volume were underestimated by a factor of two in one case and overestimated by a factor of two in the second case. Further investigation revealed that reduced leaf area associated with drought caused laser pulses to penetrate further into the canopy than expected, resulting in significant underestimation of biomass and canopy height.

Crown shape also has been shown to introduce error, especially with small footprint-based structure estimates. Nelson (1997) demonstrated that conic canopies result in lower estimates of height, biomass, and basal area than spherical canopies. Intuitively, one would expect this to be the case because the tops of conic trees provide relatively small reflectance areas compared with the tops of spherical trees. Most laser hits would occur in the lower canopy for conic species like conifers and in the upper canopy in spherical species like many broadleaf deciduous trees.

Means et al. (1999) and Cowen et al. (2000) have shown that canopy cover is related to the ratio of canopy returns/total returns. The relationship is linear, resulting in an r^2 of 0.7 to 0.9. The former authors also demonstrate that crown leaf biomass is predictable from the sum of canopy returns. Additional research (Naesset, 1997a; Means et al., 2000; Hyypä et al., 2001) demonstrates that total stand volume can be estimated effectively using a number of metrics (i.e., mean canopy height, coefficient of variation of mean canopy height), and crown volume is predictable using estimates of crown height and spatial extent of footprint (Dubayah and Drake, 2000). One might speculate that crown bulk density could be estimated by dividing crown biomass by crown volume.

Canopy height is one of the most widely studied and easily obtainable measurements (Naesset, 1997b; Magnussen and Boudewyn, 1998; Lefsky et al., 1999a, 1999b; Magnussen et al., 1999; Means et al., 1999; Rieger et al., 1999; Hyypä et al., 2000; Means et al., 2000; Naesset and Bjerknes, 2001), although the aforementioned crown shape effect, leaf area, and leaf angle serve to negatively bias height estimates. Crown base height, another significant canopy fuel metric, is obtainable by deriving a minimum height of canopy hits, assuming that there is separation between canopy base and ground (Magnussen and Boudewyn, 1998). Naesset and Okland (2002) suggest that crown base is predictable from empirical observation that the 25th percentile height of both first and last returns are correlated with this metric.

While most of the previously cited research is not directly applicable to the study of surface fuels, it generally supports the goals put forth by this dissertation in development of data processing methodology, identification of potential problems, and interpretation of results in the context of what is known about how laser radiation interacts with vegetation and ground surfaces. The bulk of the literature targets silvicultural applications (Lefsky et al., 2001), but has obvious applicability to estimation of fuel attributes, particularly those in the crown. Conspicuously absent from the literature are studies focused on surface attributes. Ritchie et al. (1992) and Weltz et al. (1994) have examined laser height measurements and variability in a rangeland setting in New Mexico and were able to show that the technology was useful for estimating height, canopy cover, and distribution of shrubs and small trees. However, this research does not translate directly into study of debris on the forest floor beneath canopies, and the most applicable literature to the problem at hand is probably the aforementioned micro-roughness research conducted on beaches and icesheets. This dissertation, then, exploits a gap in the literature by attempting to advance our understanding of how laser altimetry can be used to estimate surface fuels.

Objectives

This research seeks to answer four basic questions. Can surface fuels be remotely sensed? Which attributes of the fuel bed lend themselves to measurement? Can fuel attributes be mapped in a spatially-meaningful context to allow us to infer disturbance history? and, Is there a link between optical remote sensing data and fuel distributions?

In order to advance our understanding of surface fuel distributions and their potential relationships to photomorphic tone/texture and disturbance history, this research will:

- 1) Develop a method for processing airborne laser altimetry data that facilitates discrimination of FBPS fuel models and provides estimates of specific fuel bed parameters (load, volume, surface area).
- 2) Explore the validity of remotely-sensed fuel estimates through comparison with plot-level and area-based field estimates.
- 3) Describe the horizontal distribution of surface fuels, and examine them in the context of photomorphic tone/texture and fire history.

These objectives are addressed in the following three chapters. The chapters provide background, context, and objectives, and are essentially stand-alone, individual experiments. Collectively, they represent a cogent assessment of surface fuels in a spatial and thematic context. The element of time is tacitly introduced in the final chapter within the context of fuels and disturbance history.

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CHAPTER 2

USING AIRBORNE LASER ALTIMETRY TO DETERMINE FUEL MODELS FOR ESTIMATING FIRE BEHAVIOR

Abstract: Airborne laser altimetry provides an unprecedented view of the forest floor in timber fuel types and is clearly a promising new tool for fuels assessments. It can be used to resolve FBPS fuel models eight and ten 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: laser altimetry; fuels; fire behavior

Introduction

Accurate, spatially explicit fuels data are increasingly needed as land management agencies embrace prescribed fire and thinning as a viable fuels reduction alternatives for our forested lands. 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. First, 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. Second, an expanding urban interface and an increasingly litigious society have narrowed the margin for error in fire management decisions. Third, fire managers are now required to use complex, data-intensive fire behavior and smoke production models to support environmental assessments and burn plans. Fourth, 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 airborne laser altimetry for identifying fuel models in closed-canopy Western conifer forests.

A laser altimetry uses light emissions to measure ranges between itself and a reflective surface. An airborne instrument emits pulses of electro-magnetic 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 like slope and vegetation height are determined by analysis of 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, it is only in the last fifteen years that researchers have 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 are providing laser altimetry services worldwide (Baltsavias, 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; Pachepski and Ritchie, 1998; Magnussen and Boudewyn, 1998; Naesset and Bjerknes, 2001). Additionally, 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 in their study of surface roughness of the Greenland ice sheet. Given the obvious need for reliable fuels data from the fire and forestry communities, this compelling application is explored further here.

Approach

Fire managers use the thirteen standard fuel models of Albini (1976) along with wind, slope, and moisture data to predict fire behavior and to a lesser extent, to estimate fire effects. The fuel models are general representations of fuel beds that have specific, difficult-to-measure fuels properties like fuel load by size class, packing ratio, and surface area to volume ratio. The strength of these models is that they allow a user 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 U.S., the two most frequently used fire behavior fuel models are model eight (closed canopy short-needle conifers with light fuel loads and little undergrowth) and model ten (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 ten will burn at the upper limit of control by direct attack, while fires in model eight 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, their appearance is often 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 U.S.

For the purpose of the exploratory work presented here, the Tenderfoot Creek Experimental Forest (TCEF) was chosen as a study site primarily because it spanned the range of fuel conditions within the two fuel models described above. The TCEF is a 9125 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

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



courtesy of USDA Forest Service Fire Sciences Laboratory-Missoula

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



courtesy of USDA Forest Service Fire Sciences Laboratory-Missoula

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

stands of lodgepole to multi-storied, 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 utilizes 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 changing 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 such that the nominal footprint size was 2.95 feet and the average return density was one per eight square feet.

Laser data were extracted for thirty-three 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 using Anderson's (1982) guide by experienced fire personnel.

Canopy laser hits were separated from ground returns manually and a mean ground surface was created from the ground measurements. The height of each return above this mean 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 non-ground 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 mean ground surface demonstrate the characteristic distributions of material in the vertical domain for fuel models eight and ten (Fig. 2). Visual comparison of these height profiles with the photographs in figure one show that the laser data roughly depict a unimodal distribution of biomass in fuel model eight and a multimodal distribution in model ten. Further, a large fraction of the returns in fuel model ten come from within the fuel bed while few occur in the fuel bed of model eight. This comparison supports our intuition that fuel beds in model ten are more likely to have rough reflective surfaces relative to those in model eight, 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 eight, 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 ten 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 (Prob > F: 0.000). If we accept the validity of the obstacle density threshold above and for the moment, ignore fuel models one and two, then fuel models eight and ten can be distinguished correctly in 28 of 31 cases (90 percent). More specifically, if the landscape was composed only of fuel models eight and ten, we could correctly identify fuel model eight 89 percent of the time and fuel model ten, 92 percent of the time (producer's accuracy). The probability that an obstacle

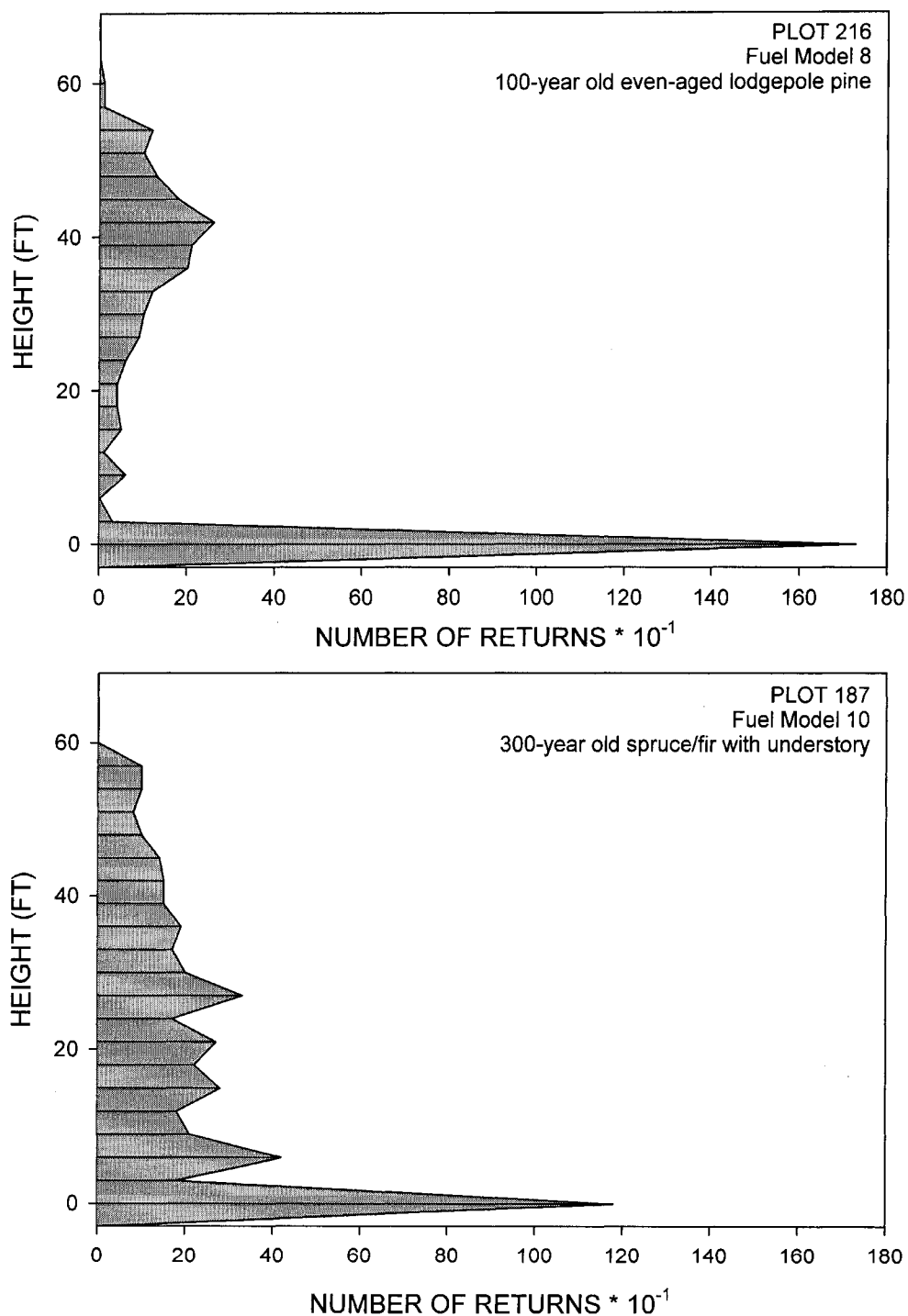


Fig. 2. Laser height profiles for two 0.10 acre plots representative of fuel models eight and ten, respectively. These are same plots depicted in the images of figure 1 above.

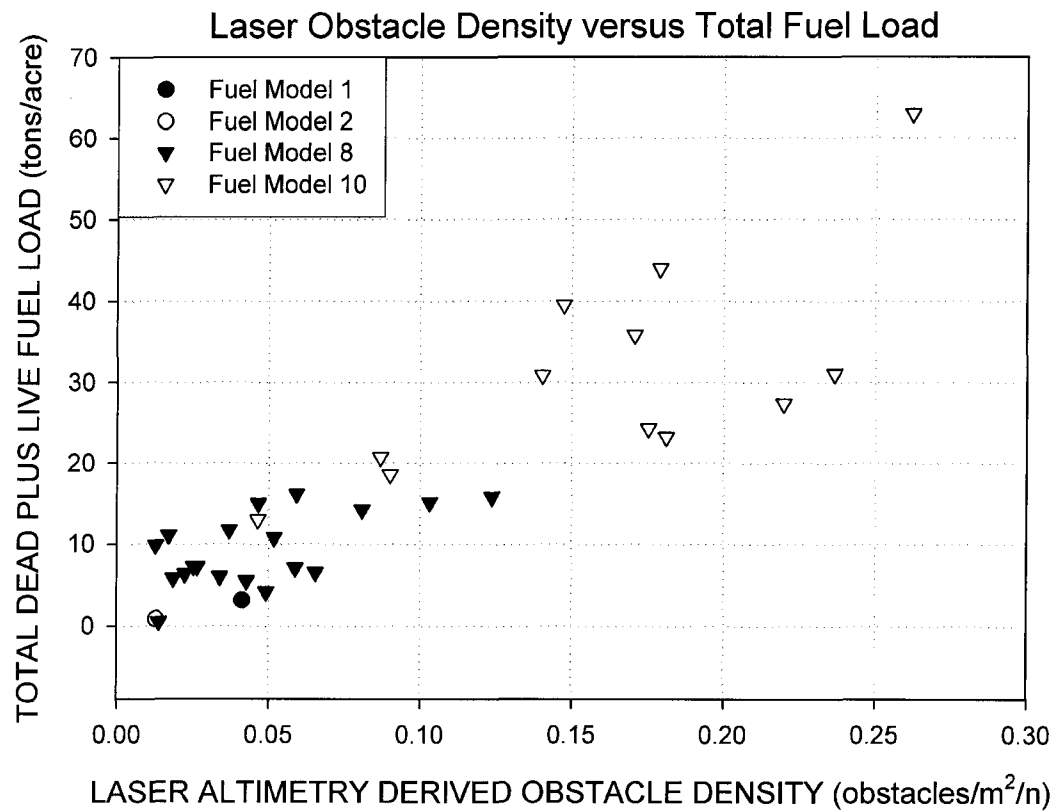


Fig. 3. Obstacle density versus total fuel load shows that fuel models with relatively light fuel loads appear smooth (low obstacle density) compared with fuel models characterized by heavier coarse woody debris loads. Further, fuel model eight can be distinguished from fuel model ten at an obstacle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

density below 0.082 is fuel model eight is 0.94 and the probability that an obstacle density above it is fuel model ten is 0.85 (user's accuracy).

In the three cases where the obstacle density threshold of 0.082 did not correctly separate models eight from ten, it is not certain that the laser altimetry estimate is wrong and the field estimate is correct. Upon post-analysis field inspection of the plots, I believe that the laser data are consistent in their characterizations of fuel models, and may have correctly identified the appropriate timber fuel models in all thirty-one 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 that vary in appearance from site to site.

A plot of dead versus live fuel for the Tenderfoot field data reveals some of this subjectivity (Fig. 4). Dead fuel load is clearly the primary observation by which field personnel distinguish fuel model eight from ten, 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 gradient, suggesting that live fuels were not a significant factor in assignment of fuel models. As a result, six of the plots that were classified as fuel model eight by field personnel contain a relatively large fraction of live, combustible biomass and relatively less dead fuel, and therefore probably do not belong in either fuel model eight or ten. Rather, they represent fuel conditions where rates of spread and fire line intensities would be characteristically low (e.g., fuel model 5), except during dry windy periods, where torching, crowning, and spotting are possible. Fuel beds like these raise one of the thorny issues in fuels mapping. That is, where does one establish breakpoints between fuel models like the ones found at Tenderfoot? 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 eights might burn like tens under the right

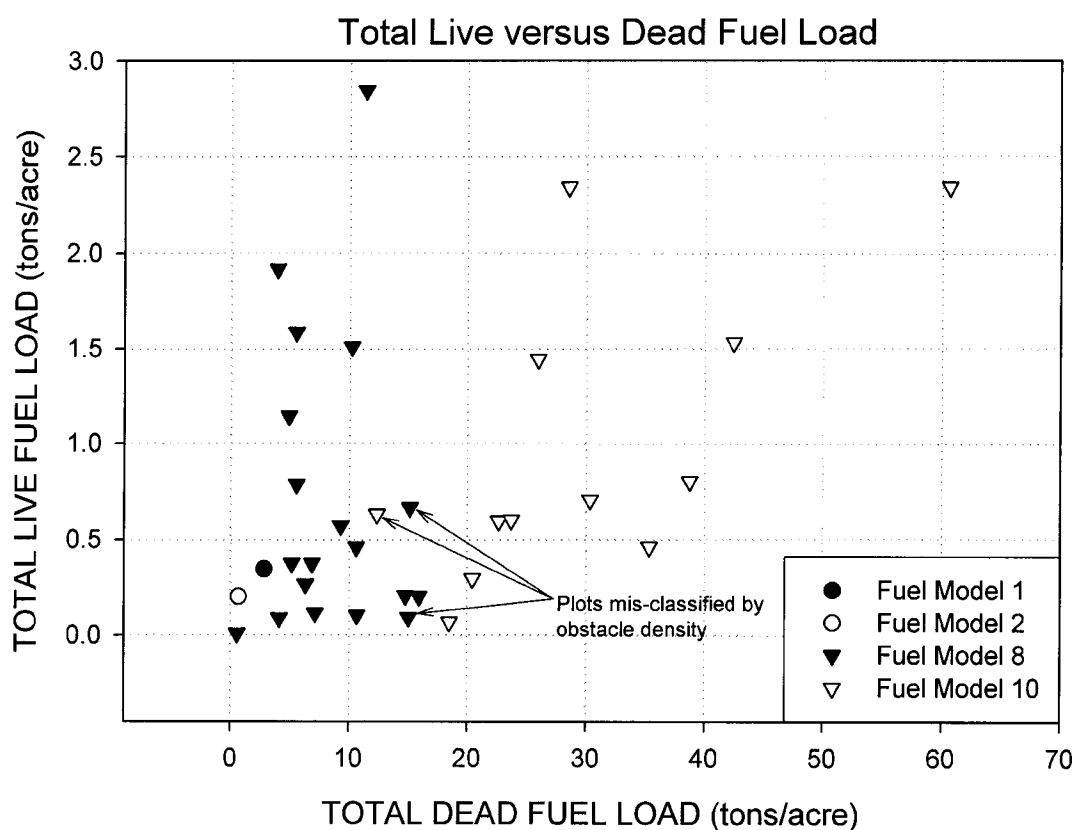


Fig. 4. Total live versus dead fuel load reveals that field fuel model classification is largely based on dead fuels. The breakpoint between these fuel models is between 13 and 16 tons per acre of dead woody debris.

conditions, and which fuel model tens might burn like one of the slash fuel models under these same conditions (i.e., what are the actual fuels at each plot?).

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 woody fuel loads directly, thereby resolving some of the breakpoint issues discussed above. Herein lies one of the more promising features of the technology; the potential to estimate fuels across a continuum, rather than having to place fuels into discrete classes. Recall that a fuel model is, in essence, a distillation of fuels attributes that govern fire line intensity and rates of spread; i.e., fuels less than three inches in diameter. Yet figure 4 has shown us that in practice, fuel model 8 is discriminated from 10 by the coarse woody debris that characteristically dominates the total dead fuel load. When combined with the discriminatory power of laser roughness described above, this observation leads one to hypothesize that laser altimetry may be effective for estimating the large fuels that contribute to crowning, spotting, and a variety of fire effects that occur after passage of the flaming front. It is less obvious whether the fine fuels that govern rates of spread contribute to laser-derived roughness, and clearly, more research is needed in this area. The relationship between roughness and fuel load does suggest that although laser altimetry is very useful for identifying fuel models in timbered landscapes with closed canopies, this is probably an underutilization of the data.

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 may 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 eight and ten, in part because these are two of the most difficult to resolve using traditional remote sensing. However, the Tenderfoot landscape is not composed only of fuel models eight and ten and the data utilized in this study contain one plot each of fuel models one (Western short grasses) and two (open timber with grass understory). Although too few in number to ascribe significance to, these data highlight several additional considerations. First, both plots have relatively smooth fuel beds and correspondingly low obstacle densities, and consequently overlap with the obstacle density distribution of fuel model eight. The laser altimetry data cannot be expected to provide differentiation between short-needle conifer litter (model 8) and short grasses (models 1 and 2) given the similarity of their reflective surfaces and the accuracy of the laser altimetry data in the vertical domain (~15cm). Additionally, the data suggest that obstacle density is primarily a function of coarse woody debris loads (>3 inch diameter pieces) that dominate the total fuel loads depicted in figure 3. Fuel models one and two, then, might best be distinguished from model eight 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 Bjerknes, 2001), lending credibility to the idea that a fuel model eight, which is characteristically closed canopied could be separated from models one and two, 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 nine (closed canopy long-needle pine litter). Model nine should look much like model eight in terms of obstacle density, but fire behavior is significantly different with model nine exhibiting consistently higher rates of spread under similar meteorological conditions.

In order to distinguish fuel model nine from model eight, 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 is difficult to tile with adjacent fuel maps because the methods and data used to create it are diverse and often unique, that is generally only useful for fire behavior prediction and not for any other purpose, and that quantifies fire behavior classes rather than direct measures of fuels (Keane et al., 1998).

Many in the remote sensing community have thought that some of the problems addressed above might be overcome through utilization of active remote sensing techniques such as laser altimetry. However, it is only recently that we have had the ability to explore the efficacy of this technology for fuel mapping. The research presented here confirms that laser altimetry can provide excellent resolving power for discrimination of fuel models eight and ten 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, I 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 the 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 the aforementioned areas. The potential ability of laser altimetry to provide canopy attributes like crown bulk density and vertical continuity of biomass that are important for predicting initiation and sustenance of destructive crown fires is significant and certainly requires further investigation. Researchers should also explore fusion of traditional optical remote sensing methods with laser data, and it is my belief that these methods will lead to an unprecedented ability to characterize the distribution of forest fuels in both the horizontal and vertical domains.

Acknowledgements

This research was supported by NASA through funding of project AFRR-000-0175 and by the USDA Forest Service Rocky Mountain Research Station through RJVA 00-JV-112220-48-018. The author wishes to thank the Tenderfoot Creek Experimental Forest and the Lewis and Clark National Forest for logistical support. Thanks also to the USDA Forest Service Fire Sciences Laboratory in Missoula for collection of fuels data.

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CHAPTER 3**ESTIMATING SURFACE FUEL ATTRIBUTES WITH AIRBORNE LASER ALTIMETRY-DERIVED SURFACE ROUGHNESS**

Abstract: Laser altimetry-derived measures of surface roughness can be used to estimate fuel volumes and surface areas with excellent efficacy beneath closed-canopied lodgepole pine (*Pinus contorta* Dougl. ex Loud.) forests in west-central Montana, U.S.A. Obstacle density, standard deviation of the ground-height distribution (GHD), and kurtosis of the GHD correlate highly with field estimates of fuel volume/surface area. These relationships can be exploited to predict fuel volumes and surface areas at the plot-level ($r^2 \sim 0.8$). The observed relationships are driven by coarse woody debris in the fuel bed, and not by live biomass or smaller dead fuels. Further, it appears that surface roughness does not depict discreet fuel entities, but rather that woody debris causes scattering of incident laser radiation such that the apparent ground surface of heavily loaded plots is highly variable relative to those with less fuel accumulation. These results suggest that laser altimetry is a valuable tool for mapping surface fuels in heavily forested areas and is capable of filling the growing gap between the needs of those concerned with fire behavior and those concerned with fire effects by providing accurate estimates of the coarse woody debris that affect smoke production, duff consumption, soil exposure, and heat transfer to the soil.

Introduction

The mathematical spread model, BEHAVE (Rothermel 1972), recast the concept of fire behavior prediction by making possible quantitative estimates of fire line intensity and rate of spread in homogenous surface fuel beds. With the development of BEHAVE came the need for consistent, numerical measurements of fuel properties. Brown (1970, 1974) and Brown et al. (1982) proposed field inventory procedures that involved counting and measuring pieces of wood along line transects to quantify coarse woody debris volumes, and Albini (1976) created generalizations, or models of fuel components, to summarize burning characteristics for representative fuel types. In essence, these models distilled complex fuels landscapes into numerical BEHAVE inputs.

Although the field methods of Brown et al. (1982) are still widely used today (Keane et al. 1996), they are time consuming and not efficiently applied to large landscapes. The photo series (e.g. Fisher 1981) attempted to address these shortcomings by providing oblique photographs of fuel complexes whose attributes had been measured, for visual comparison with field plots. This approach, where fuels are estimated but not actually measured, is probably the source of orders-of-magnitude more fuels information than field sampling. The thirteen standard fuel models of Albini (1976) were incorporated in a similar photo-guide by Anderson (1982) and now provide the basis for much fire behavior fuels mapping. Certainly, many fire managers view their respective units in terms of these models, but have not actually sampled most of the fuel beds being classified. However, Lutes (1999) showed that the photo-series approach consistently provided less precise estimates for volume of down woody debris than did the line intercept method and, ironically, was often no faster than this method, particularly for those plots characterized by lighter fuel loads.

Historically, then, fuel measurements have been driven by fire suppression and fire danger rating needs with the goal of predicting spread rates and intensity. Calculations of rates of

spread are weighted toward the fine fuel classes that carry the flaming front. Flame length, which traditionally has been used to rate the difficulty of control with specific suppression resources, also has been used to examine scorch height and tree mortality (Andrews and Chase 1989; Reinhardt et al. 1997). In general, however, traditional fuels quantification has not provided measures of fuels attributes necessary for estimating many fire effects. Specifically, the amount and condition of coarse woody debris and duff are absent from the fire behavior fuel models. Although consumption of coarse woody debris affects duff consumption, soil exposure, heat transfer to the soil, and smoke production (Reinhardt et al. 1991), this element of the fuel bed has been neglected because it is not often important to fire spread. Further, the concept of residence time, which relates to soil and cambium heating, fuel consumption, and smoke production, is not directly addressed by the models that focus on combustion in the flaming front.

In sum, the traditional methods used to map fuels in the field do not characterize the fuel bed effectively for a growing number of fire effects applications and are labor-intensive, time-consuming, expensive, and necessarily restricted to small geographic areas. As a consequence, many land management agencies have not developed fuels maps for entire administrative units, instead mapping fuels in smaller areas as specific projects are developed and implemented. For example, fire behavior fuel model polygons are often delineated as part of a burn plan prior to initiation of a prescribed fire only for the specific slopes or drainages that are under treatment. In such cases, polygon boundaries are usually identified by eye from air photos and traced by an experienced fire or fuels specialist. Plot data, topographic maps, and field observations are often used as aids, but the resulting fuels map is generally the product of a management officer's impression of the area. This approach is appropriate and effective in many cases primarily because it draws upon the major strength of any unit- the field experience of its personnel. However, air-photo delineation of fuel types is limited to visually-determined canopy textural

differences (Lillesand and Kiefer 1994), and thus, does not usually provide information from the forest floor.

Although optical remote sensing techniques have shown promise for mapping fuels, their inability to provide consistent spectral information beneath forest canopies has restricted their ability to characterize surface fuels accurately (Keane et al., 1998). While discrimination between some forest stands is possible (Jakubauskas 1996; St-Onge and Cavayas 1997), most of the fuels attributes of these stands cannot be assessed because there is no predictable link between the distributions of surface fuels and the distribution of stands. Consequently, remote sensing images are often used like the photo guides of Fisher (1981) or Anderson (1982), where an analyst assigns fuels characteristics to areas from photos or images that may or may not contain appropriate information content. In photo series, the transformation from images to fuels is possible because the interpreter can see many of the individual fuels entities that are being quantified in both the photo and on the ground. In remote sensing, however, the images often contain little information about the fuels of interest because these fuels are obscured by vegetation canopies or are distributed at resolutions finer than the instantaneous field of view (IFOV) of the sensor.

Remote sensing-based fuels mapping has consequently begun to rely on models that link site biophysical attributes to fuels attributes via integration of ancillary data sets like land cover type, potential vegetation, and structural stage (Keane et al., 1998). These efforts have met with modest success but have been hindered by the same issue discussed previously. Namely, a site's biophysical attributes are not predictably related to surface fuel distributions.

Clearly, then, new approaches to fuels mapping are needed. Airborne laser altimetry is one of the most promising tools for this endeavor because it has the potential to provide information from within and beneath tree canopies. Laser altimetry has been shown capable of providing relatively precise measurements of canopy height, vertical canopy distribution, surface

roughness, and ground surface topographic elevation (Nelson et al. 1988a; Nelson et al. 1988b; Ritchie et al. 1992; Weltz et al. 1994; Nilsson 1996; Naesset 1997; Nelson et al. 1997; Magnussen and Boudewyn 1998, Naesset 1999; Naesset and Bjerknes 2001). More recently, this technology has been used successfully to identify U.S. Fire Behavior Prediction System (FBPS) fuel models in closed canopy Western conifer forests (Seielstad and Queen, in review). These authors demonstrated that laser altimetry-derived surface roughness was closely linked to the woody debris loads characteristic of FBPS fuel model 8 (closed canopy short-needle conifer with little undergrowth or dead/down woody fuels) and fuel model 10 (closed canopy with understory and a heavy dead/down component) in such a way that discrimination was possible. Further, surface roughness appeared to be related to specific fuel properties, suggesting that direct estimates of woody debris loads/volumes were obtainable with laser altimetry.

In the study presented here, I explore the relationships between airborne laser altimetry-derived surface roughness and field-measured surface fuels attributes at the Tenderfoot Creek Experimental Forest in west-central Montana, U.S.A. The idea that surface roughness might serve as a proxy for fuel volume is intuitive, yet it is still unclear whether laser altimetry derived roughness beneath a forest canopy is meaningful in this context. Seielstad and Queen (in review) suggested that roughness is directly related to fuels characteristics, thus providing foundation for the following research.

Material and methods

Study site

The Tenderfoot Creek Experimental Forest (TCEF) is a 3693 ha forest located on the Lewis and Clark National Forest (Kings Hill Ranger District) in the western Little Belt Mountains, Montana (Fig. 1). It lies at 2100 meters elevation on a sloping basin of quartzite and sandstone beds that are intermittently overlain with clays. The impermeable bedrock features

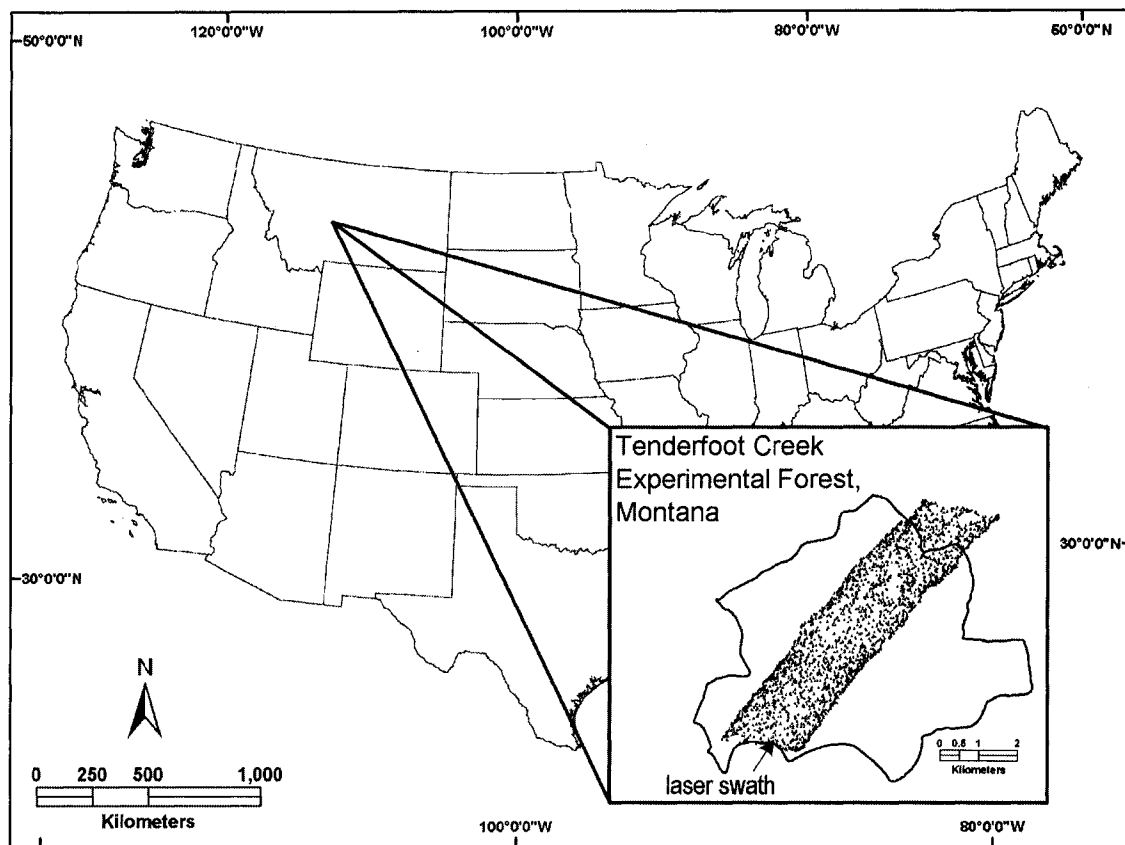


Fig. 1. Study site location.

have resulted in numerous springs and open wet meadows in the mid-slope portions of the study area that drain into Tenderfoot Creek and ultimately into the Smith River, approximately 27 km downstream (McCaughey 1998). Even-aged and multi-aged stands of lodgepole pine (*pinus contorta* Dougl. ex Loud.) dominate the region, interspersed with older stands of subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.) and Engelmann spruce (*Picea engelmannii* Parry ex Engelm.). These patterns reflect a complex fire history, which has been documented by Barrett (1993) through dendrochronology and air-photo interpretation. A heterogeneous mix of age classes reflects a series of mixed-intensity fires. The TCEF has not experienced a significant fire in 120 years and consequently, a large fraction of its forests are now characterized by older age classes susceptible to stand replacing fire. Stand heights range from 16-24 meters and stand densities from 400-2100 stems/ha.

From a fuels standpoint the TCEF is composed mostly of Albini's (1976) fuel model eight and fuel model ten with loadings ranging from 0.1 to 14 kg/m². Regeneration ranges from none in the younger lodgepole stands to heavy in older stands. In the latter stands, a spruce/fir understory is approaching two meters in height and is growing in virtually impenetrable thickets. Overall, the TCEF is an excellent laboratory in which to test the efficacy of laser altimetry-based fuels measurements because it spans a broad range of possible fuels conditions for closed canopy Western conifer forest types.

Field data acquisition

The field data used in this investigation were collected at gridded, permanent plot locations in 1997/1998 following ECODATA protocols (Hann et al. 1987; Keane et al. 1990; Jensen et al. 1993). For each 404 m² (0.10 acre) circular plot, surface fuels were sampled after Brown (1974) along five transects (transect lengths: 1-hr 1.83m, 10-hr 1.83m, 100-hr 3.05m, 1000-hr 15.25m), each transect offset by 60 degrees from the previous transect. Fuel volumes,

surface areas, and loads were calculated using standard U.S. fire behavior timelag conventions (1-hr fuels (0-0.635 cm), 10-hr fuels (0.635-2.54 cm), 100-hr fuels (2.54-7.62 cm), and 1000+ -hr fuels (>7.62 cm)). Brown's (1974) line intercept approach assumes random piece distribution and orientation, assumptions that were tested by Lutes (1999) in the Tenderfoot Creek Experimental Forest. Lutes (1999) found that the line intercept method was an unbiased estimator of coarse woody debris on 0.25 ha plots, despite an element of non-randomness in piece orientation. He suggested that placement and length of line can reduce bias caused by both non-random distribution and orientation, a consideration Keane et al. (1990) incorporated in the ECODATA protocols through the use of multiple, differentially-oriented transects. Comprehensive tree data were also collected on each plot for all trees, and leaf, branch, and stem biomass were calculated from them using equations presented by Moeur (1981) and Ter-Mikaelian and Korzukhin (1997). Additionally, fuel bed depth, quadratic mean fuel depth, duff depth, shrub depth, and shrub ground coverage data were collected.

Airborne laser data acquisition

Laser altimetry data were obtained on October 10-13, 1999 with an Aeroscan LIDAR (light detection and ranging) system contracted through Spencer Gross Engineering, Inc. The system, mounted on a Piper Navajo Chieftain aircraft, included a laser transmitter and receiving optics, an inertial measurement unit (IMU), and a dual frequency GPS receiver and antenna. The laser operates at 1064 nm wavelength, scanning across track using a bi-directional oscillating mirror, resulting in a sinusoidal pattern of points along each flightline. Up to five echoes per pulse are recorded with a minimum vertical separation between echos of 2-5 meters. At TCEF, the laser was pulsed at 15 kHz at a peak power of 11.7 kW with a pulse width of 11.8 nanoseconds. Specific acquisition parameters were as follows- flying height 2743 meters above mean terrain (AMT); airspeed 110-130 knots; laser pulse rate 15 kHz; scan field of view 5

degrees; scan rate 25.0 Hz; average swath width 240 meters; nominal footprint size 0.90 meters; average ground return density 1.5 returns/m².

Lidar, IMU, and GPS data were correlated using GPS time and processed by the vendor to produce an ASCII mass point file of x,y,z on the UTM projection. The vendor corrected all ranges for atmospheric refraction and transmission delays. During the data collection itself, an additional GPS receiver was in operation at a survey control point at Great Falls International Airport, 40 km away. A kinematic survey of several paved roadways was also conducted within the project area. Comparisons of data from flightline to flightline and against the kinematic survey resulted in the following- vertical accuracy 14.5 cm RMSE; standard deviation 10.2 cm; mean difference 10.4 cm; horizontal accuracy 180 cm.

Data processing

Thirty-three plots were selected for this study spanning the range of fuel conditions observed at Tenderfoot. Plot centers with positional accuracies in the ± 3 meter range were marked using both PLGR and Centurion GPS receivers. Selection of plots within each fuel condition was random, but plots located near an 'edge' where fuel conditions changed significantly over short distances were not selected. For lack of terminology, this meant that each plot used in the study was located near the center of what one might consider a fuel 'stand'. The idea here was to minimize the effects of possible mis-collocation between the laser data and the plots. The results presented hence, then, are based on the assumption that the fuels found in a three to five meter buffer area around each plot are the same as those in the plot itself, an assumption tacitly validated by the author when plots were selected.

For each plot, a circular cloud of laser returns roughly twice the size of plot dimensions was extracted from the mass point file of all returns. Each plot contained 2500–7500 individual returns, the number of returns a function of proximity to the edge of a flightline and to complexity

and height of the vegetation overstory. The clouds of lidar points were separated into canopy returns and ground returns with the goal of characterizing in best possible fashion those returns that were near ground but not on the ground (i.e. the fuel bed). This required manual separation (Huising and Pereira, 1998; Wehr and Lohr 1999), as existing automated canopy-ground separation inadvertently considered as ground returns many of the points critical to this investigation (near-ground returns).

Manual discrimination of canopy points from ground points was achieved in the following way. The height of each point above datum was plotted as a function of distance from a point of origin located along the track of the laser. The subsequent profiles clearly depicted the ground surface below a scatter of canopy points. Separation was then carried out using the point file edit features of a Geographic Information System (GIS) software package.

Following canopy-ground separation, a mean surface was calculated from the ground points for each plot using an 8 m x 8 m moving filter. The height above ground for each point was then calculated as the difference from that surface. Points within the actual plot dimensions were then extracted and all points within two meters of the ground were considered ‘hits’ within the fuel bed, utilizing the published maximum fuel bed depth for the 13 fire behavior fuel models (Anderson 1982). These points form the basis for generation of the roughness metrics discussed below.

Approach

The notion that measurements of surface roughness can be linked to fuels attributes like volume, surface area, load, or fuel bed depth is intuitive. Ground/near-ground surface roughness is expected to be a function of the relative presence or absence of woody debris, tree/shrub regeneration, and geomorphic roughness. It seems unlikely that laser altimetry should be able to discriminate between the various components that create rough surfaces, but it may provide a

measure of roughness that is related to the previously mentioned variables. The challenge has been to derive appropriate ‘roughness’ metrics from the altimetry data with which to test these hypotheses. One metric proposed in the aerodynamic roughness literature is obstacle density (de Vries 1999). It was not specifically intended for the purpose at hand, but provides a useful starting point from which characterization of surface fuels becomes possible.

Obstacle density (OD), as it is used here, is defined as the number of non-ground laser returns in the fuel bed per unit area, normalized by the total number of returns (ground + fuel bed). It is hypothesized that OD should rise, at least to a point, as the dead/down woody debris load and/or live biomass in the fuel bed increases. Two additional metrics, standard deviation and kurtosis of the ground/near-ground height distributions (GHD) also are employed to take advantage of the fact that the distributions of ground/near ground points are approximately normal. The specific shapes of these distributions might therefore illuminate between-plot surface feature differences. For example, a site with a heavy dead/down wood component should have a platykurtic distribution compared with a more leptokurtic distribution for a site with a smooth, grassy understory (Fig. 2).

Finally, the roughness metrics described above were compared with field measurements of fuels attributes. The goal was to explore the efficacy of laser altimetry-derived roughness as a surrogate for various fuels measurements in as simple a manner as possible in order to demonstrate the validity of this approach. Consequently, all of the relationships presented are univariate correlations, whose predictive powers are tested with data held back from ten randomly selected plots.

Results

Results are organized as follows: 1) laser roughness and coarse woody debris; 2) laser roughness and live biomass; and 3) laser roughness and noise artifacts. From the outset, it is

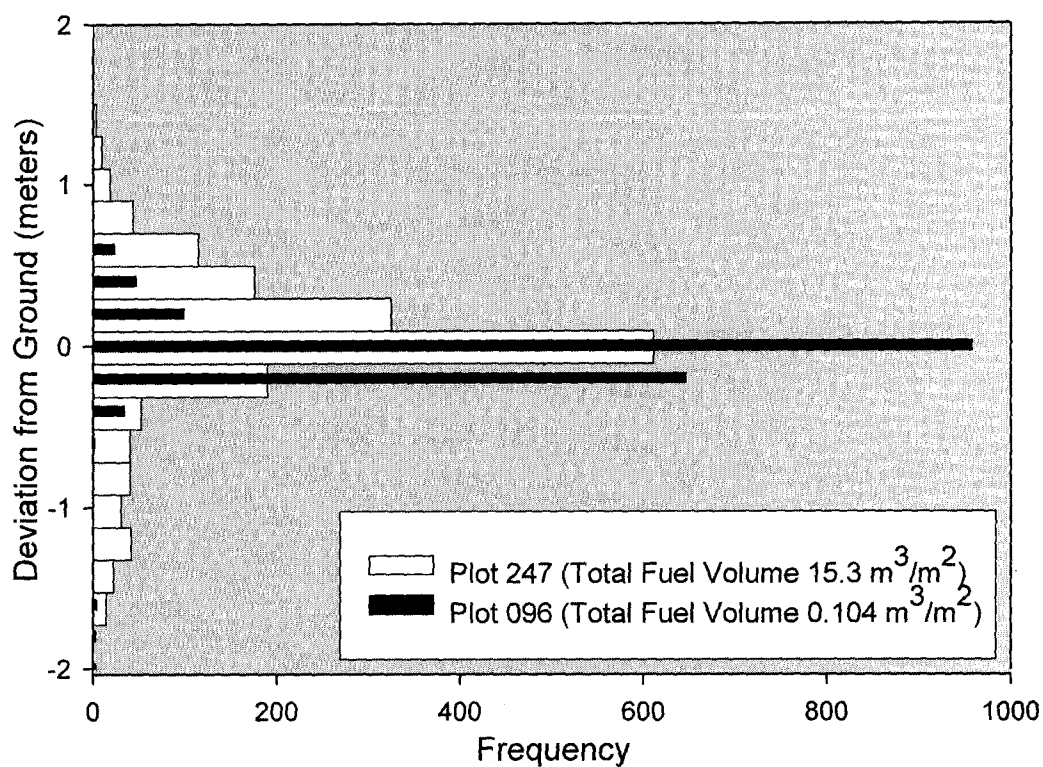


Fig. 2. Ground Height Distribution (GHD) profiles from ground/near ground laser returns for two representative plots at Tenderfoot Creek Experimental Forest. The distribution of returns spreads with heavier fuel volumes (e.g. Plot 247) and is narrower and more peaked when the forest floor contains little debris (e.g. Plot 096).

important to recognize the inter-relationships between the fuels variables that are being compared with laser-derived roughness estimates. Fuel loads and volumes are highly correlated, where deviations away from a one-to-one line are a function of the wood ‘soundness’ estimates that are incorporated into fuel load measurements (Fig. 3). As the laser altimetry data cannot be expected to account for variations in the density of individual pieces of wood, fuel volume estimates are presented rather than load estimates where appropriate. For those more comfortable working with fuel loads rather than volumes, it is worth noting that: (1) the load-volume r^2 is large, and (2) the results using either metric are virtually identical given the load-volume inter-correlation described above.

A second noteworthy feature of the fuels data is that the 1000-hr fuel volumes proportionally dwarf both the 1-100 hr volumes (1 + 10 + 100-hr fuels) and the live biomass on most plots, particularly on those with large total volumes (Table 1). Therefore, it is difficult to separate the relative contributions of these components to laser-derived surface roughness (i.e., volumetrically, heavy fuels will contribute most to the observed relationships). We generally observe strong relationships between 1000-hr volume and surface roughness and between total fuel volume and roughness, the latter relationship a function of the dominance of coarse woody debris in the total volume. The relationships between fuel surface area and roughness are more meaningful when we try to compare fuels of different size classes because the small and large fuels contribute more-or-less equally to total fuel surface area.

Table 1. Summary Statistics for Ratio of 1000-hour Fuel to Total Fuel for Load, Volume, and Surface Area.

| Fuel Metric | Min | Max | Mean | Std Dev. |
|--------------|------|------|------|----------|
| Load | 0.41 | 0.98 | 0.81 | 0.15 |
| Volume | 0.55 | 0.99 | 0.87 | 0.12 |
| Surface Area | 0.08 | 0.76 | 0.40 | 0.15 |

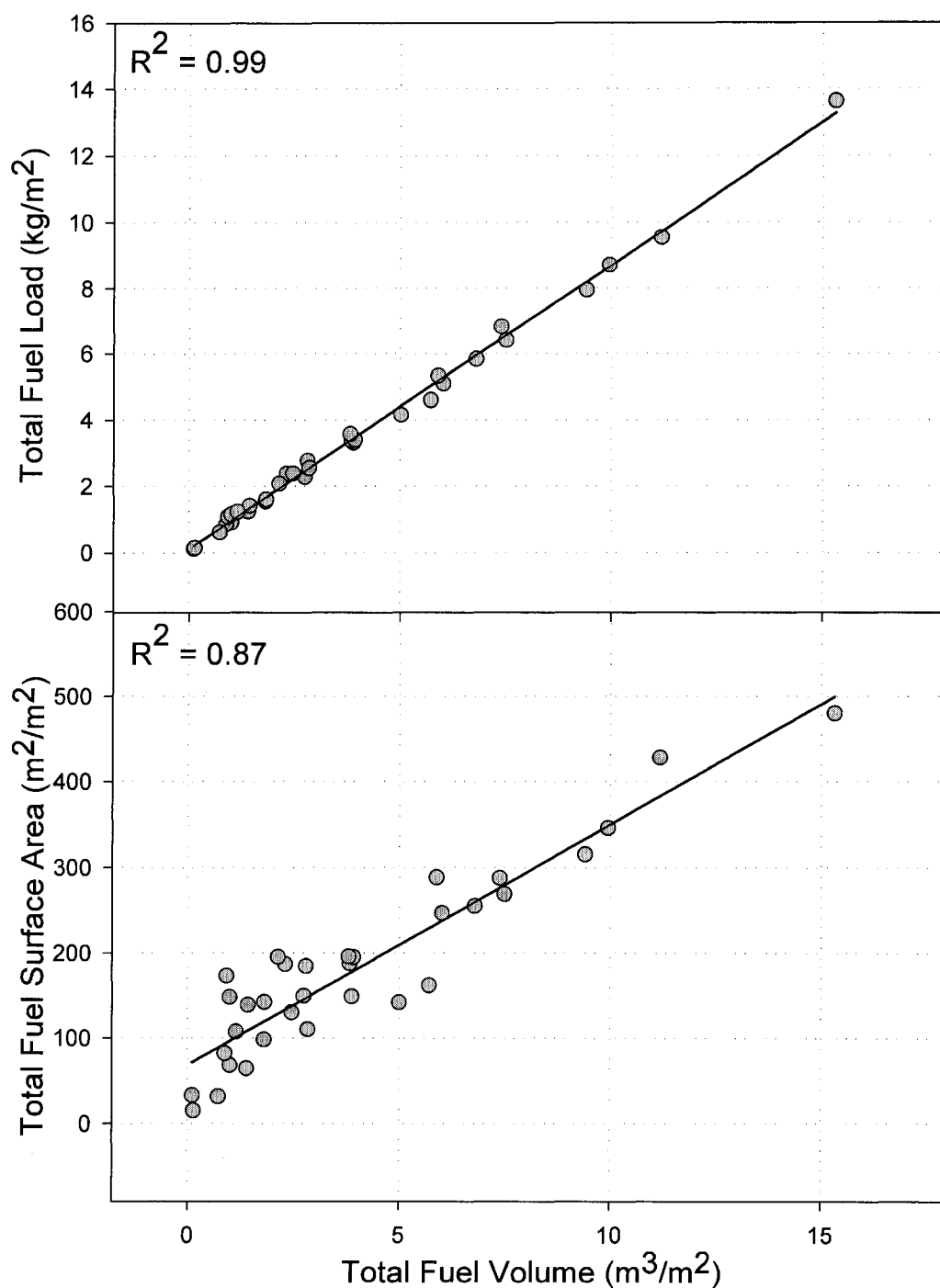


Fig. 3. Fuel metric comparisons. Variations in fuel load/volume are attributable to wood density estimates used in the load calculation. Surface area/volume deviations are caused by variable distributions of fuel size classes, which exhibit significantly different surface area-to-volume ratios.

Finally, the roughness metrics (obstacle density, standard deviation of GHD, and kurtosis of GHD) convey similar information with regard to surface roughness. Obstacle density is perhaps the most intuitive of these metrics when one considers how roughness might relate to fuels attributes. However, it is also the most difficult and time consuming to calculate, and is perhaps more susceptible to instability at low post density. Given similar performance of the roughness metrics, then, the standard deviation of GHD is probably the most desirable because it is easy to generate and is relatively robust at lower post density.

Woody debris estimates

Fuel volume

Obstacle density (OD), standard deviation of ground height distribution (δ GHD), and kurtosis of ground height distribution (KGHD) each can be used to estimate total dead fuel volume and 1000-hour fuel volume (>7.62 cm diameter pieces) with surprising efficacy (Fig. 4). Laser-derived estimates are within ± 25 percent of field measurements at each of the plots tested, although model performance is clearly better at lower fuel volumes (e.g., $< 7 \text{ m}^3/\text{m}^2$). As was previously noted, from a volumetric standpoint the total fuels are dominated by 1000-hr fuels, hence the similarity of the total fuel and 1000-hr fuel plots in Figure 4. Conversely, none of the roughness metrics provide useful predictive power for estimating the smaller diameter fuels (1-100-hr), suggesting that most of the reflective surfaces within the fuel beds that contribute to laser-derived roughness are the relatively large diameter logs that dominate the fuel assemblages. Given that total fuel volume is dominated by large diameter pieces, this finding is not surprising.

These results are remarkable especially when one considers the potential error inherent in field sampling fuels by the line intercept method. Pickford and Hazard (1978) have demonstrated that approximately 1200 meters of line is required to achieve confidence intervals better than ± 25 percent at the 95 percent interval for fuel beds with loads similar to those found at Tenderfoot.

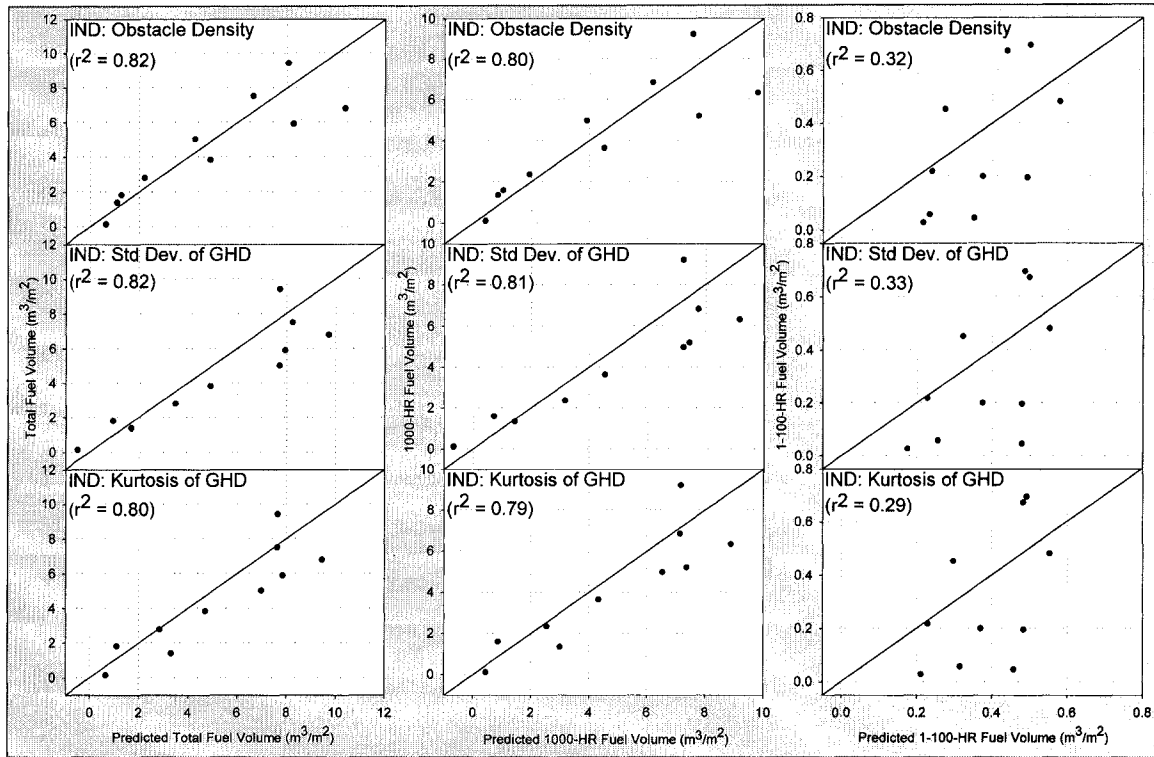


Fig. 4. Observed versus predicted plot-level fuel volume estimates for total volume, 1000-hr, and 1-100hr fuels from obstacle density, standard deviation of ground height distribution (GHD), and kurtosis of GHD. 1:1 lines depicted in each scatterplot.

For this study, we used 76.25 meters of line per plot. Further, the sample size necessary for a specified precision increases substantially as piece density decreases. Although Lutes (1999) showed statistically that the line intercept method was an accurate and unbiased estimator of fuel loads at Tenderfoot on 0.25 ha plots, his estimates were better than ± 10 percent of actual fuels only at volumes exceeding 139 m³/ha. At lower volumes, estimates ranged from ± 25 percent to ± 80 percent of actual fuel volumes with no discernable volume-dependent pattern.

Given these findings then, we can draw several tentative conclusions regarding the laser-derived estimates of fuel volume. First, although it may seem improbable that a relationship between laser roughness and field estimates is observable given the above factors, the fact that there is a strong relationship suggests that both laser and field measurements are relatively consistent. Second, the deviations of points away from the one-to-one lines observed in figure 4 are as likely a function of error in field measurements as they are in laser roughness estimates. It is entirely possible that the laser estimates of fuel volume are more consistent and accurate than those obtained by the line-intercept method. Certainly, further testing that uses actual measurements of every piece of wood on these plots would clarify this issue, recognizing that the field component of these tests would be costly and time consuming. Alternatively, simulations via a radiative transfer model may facilitate the same tests, although a better understanding of how laser radiation interacts with fuel beds is necessary prior to pursuing this line of thinking. For the moment, however, we can conclude that the observed relationships are not coincidental, and that laser-derived surface roughness can be used effectively to estimate coarse woody debris loads that are consistent with those provided by the line intercept method.

All three of the laser roughness metrics provide similar predictive power for estimating total and 1000-hr fuel volumes, as each conveys more or less the same information. The distribution of ground/near ground points does indeed spread at higher fuel volumes resulting in

distinctly platykurtic histograms as expected, and the larger standard deviations associated with these distributions are reflected in the δ GHD model. Arguably, obstacle density is the better metric at higher fuel volumes and standard deviation is more effective at lower volumes. However, given the small differences in performance of these models, δ GHD is perhaps the best roughness metric simply because it is faster and easier to calculate than either OD or KGHD.

Fuel surface area

The three roughness metrics provide equally effective estimates of fuel surface area (Fig. 5). Of all the relationships tested in this study, the strongest was between laser-derived roughness and 1000-hr fuel surface area. Total and 1-100-hr surface area was less effectively estimated for a variety of reasons. Unlike volume, the total surface area is made up of roughly equal proportions of large diameter fuels and small diameter fuels, as the small fuel particles exhibit exceptionally high surface areas relative to their volumes. Consequently, the comparison of model results between 1000-hr and 1-100 hr fuels is noteworthy. The 1000-hr fuels still provide most of the reflective surfaces contributing to the laser roughness metrics even though the gross surface area of the smaller fuels are similar in magnitude. This probably occurs for three reasons. First, many of the smaller fuels lie on the ground surface itself and are effectively indistinguishable from the ground by laser altimetry. Second, a significant fraction of the fine fuels are grasses, and are thus oriented vertically and do not provide good reflective surfaces. Third, the smaller fuels tend to scatter incident radiation more effectively than large fuels, resulting in at-sensor return intensities that are often too weak to trip the receiver.

Live biomass

The contribution of live biomass (leaf, stem, branch) to characterization of fuel bed roughness is difficult to assess in close-canopied Western conifer forests in general because the dead fuels proportionally dwarf live fuels in most instances. At Tenderfoot, the fuel beds of eight

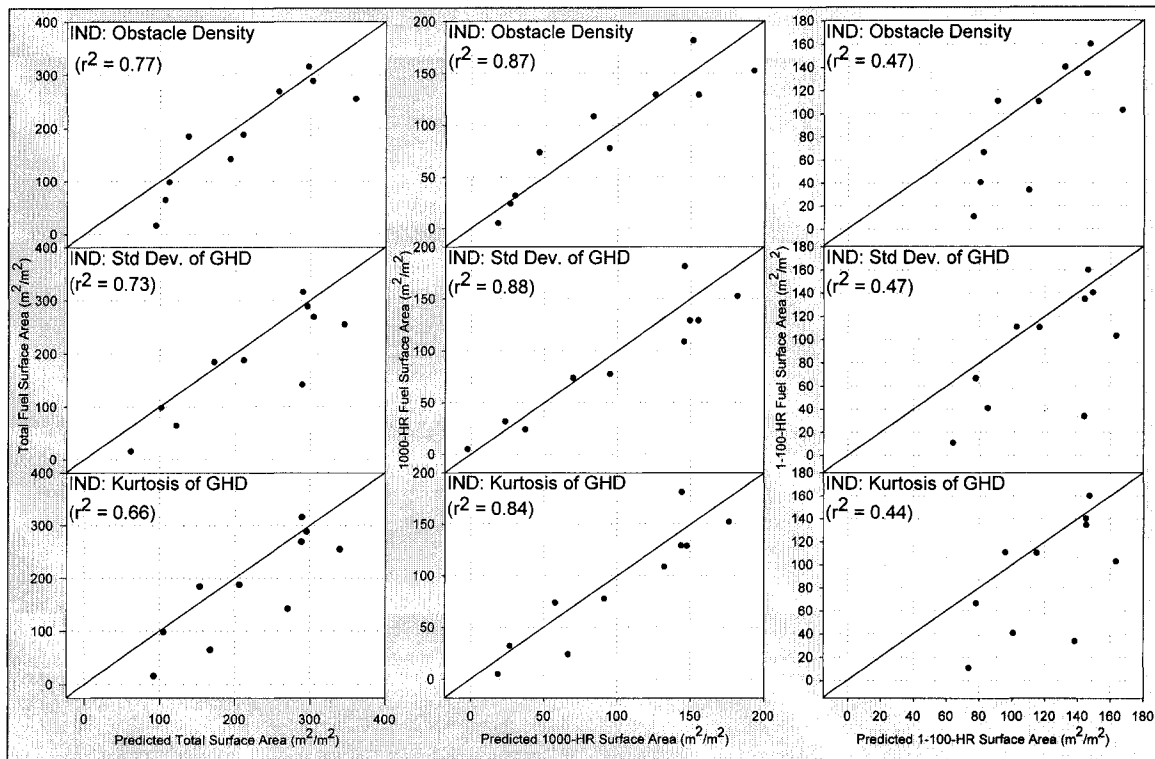


Fig. 5. Observed versus predicted plot-level fuel surface area estimates for total surface area, 1000-hr, and 1-100hr fuels from obstacle density, standard deviation of ground height distribution (GHD), and kurtosis of GHD. 1:1 lines depicted in each scatterplot.

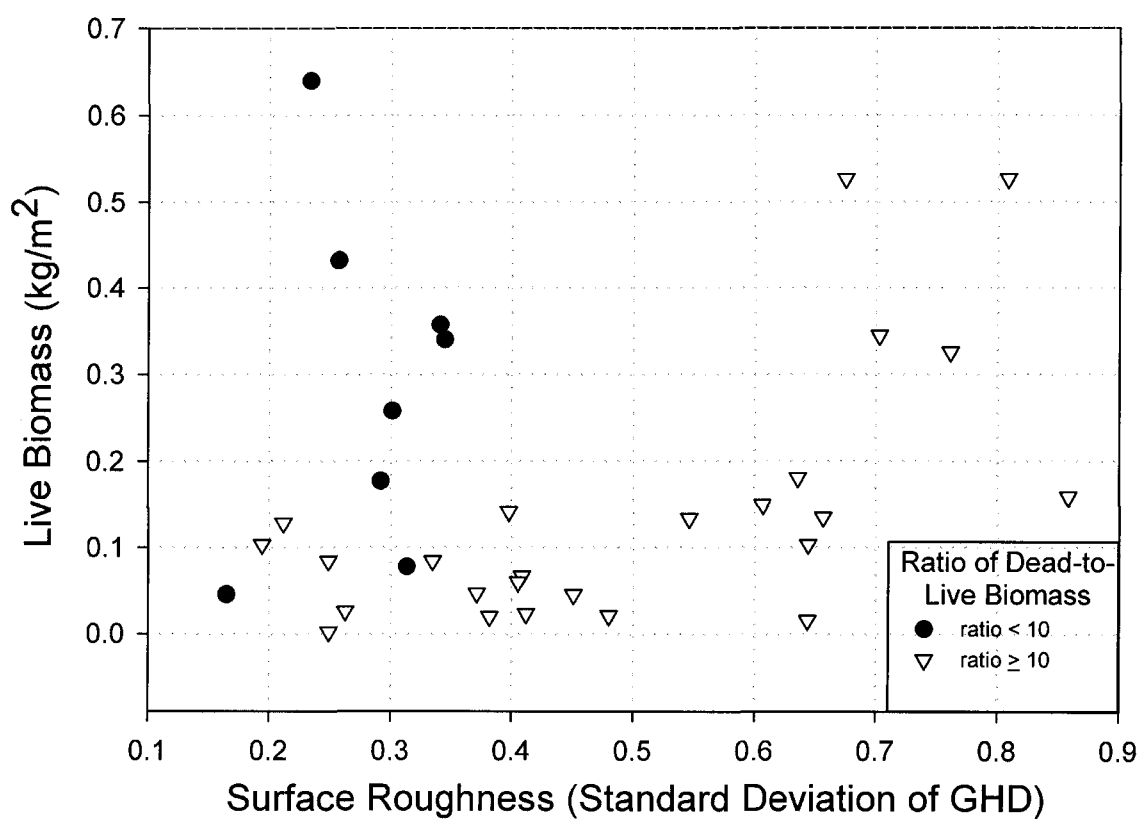


Fig. 6. Laser-derived surface roughness has a positive relationship to live biomass when the fuel bed also contains a significant fraction of dead fuel (open triangles), but the two are unrelated at lower dead fuel concentrations (filled circles).

of the thirty-three plots used in this study exhibited a ratio of dead-to-live biomass less than ten, and of these, only three had ratios less than four. However, a plot of surface roughness against live biomass in the fuel bed reveals a positive relationship for the plots that contain a significant fraction of dead fuel (Fig. 6). On plots where dead fuels make up a relatively smaller proportion of the total fuels, no relationship is observed. Regardless of the form of the live biomass/roughness relationship (e.g., linear or power), it is clear that large dead fuels are the primary contributor to roughness. Interestingly, the outliers (the four filled circles in the upper left of the Figure 6) are the plots on which the live component is largest relative to the dead fuels. We might tentatively conclude, then, that live leaf, stem, and branch biomass in the fuel bed do not contribute significantly to laser roughness for the fuel beds found at Tenderfoot.

These results suggest that roughness as measured by the Aeroscan sensor used in this study, is primarily a function of the amount of 'hard-target' in the fuel bed. Foliage, stem, and branch biomass of a conifer understory do not appear to provide consistent reflective surfaces for the incident laser radiation. In laser-based canopy height recovery studies, several authors have shown that the shape of tree crowns, the density of leaves and stems, and their arrangement and orientation cause most first-return laser data to occur at some distance into the canopy rather than from the canopy's highest surfaces (Nilsson 1996; Naesset 1997; Nelson et al. 1997; Magnussen and Boudewyn 1998; Magnussen et al. 1999; Naesset and Bjerknes 2001). Naesset (1997) showed that laser mean tree height underestimates ground measurements of tree height by 4.1-5.5 meters and Nilsson (1996) showed that it underestimates tree height by 2.1-3.7 meters. It seems likely then, that live vegetation in a two-meter-deep fuel bed would most often be transparent to the laser sensor. Consequently, we can hypothesize that the forest floor beneath a stand with a dense understory of seedlings and saplings and little coarse woody debris would appear relatively smooth, as most of the returns from this domain would be ground returns. It is only when coarse

woody debris is added to the fuel bed that we would expect to see variability in the ground/near ground returns.

Negative noise

A feature of the Tenderfoot laser altimetry data is a spatially irregular pattern of ‘pits’, or reflections that occur below the ground surface. In places, these pits are as much as five meters below ground surface and they occur with a frequency ranging from 3-17 percent of total returns. Collectively, they are termed ‘negative noise’ by the data provider. The presence of negative noise significantly complicates separation of canopy from ground, particularly when using an automated approach, and requires an additional processing step prior to this procedure. For this study, pitting was removed and the results presented above come from a noise-free data set.

Upon closer evaluation of the spatial distribution of pitting, however, a pattern emerged that suggested that the negative noise was not noise in the traditional sense of the word. Rather, pitting appears to be an artifact of laser interactions with complex fuel beds. Plots with large fuel volumes have a much higher incidence of noise than plots with small fuel volumes, and in those plots with no coarse woody debris, pitting rarely occurs. Figure 7 depicts the relationship between the frequency of noise at a site and total fuel volume. The FBPS fuel models are included in this figure to demonstrate the close links between model, total fuel, and pit frequency, and to provide the basis for a statistical evaluation of the significance of pitting as a function of fuel bed characteristics. An analysis of variance (ANOVA) shows that the variance of between-fuel model pit frequency greatly exceeds within-group variance (F ratio: 23.486) and that the two samples of fuel models have been drawn from different populations (Prob>F: 0.000).

It is this author’s belief that the rough surfaces provided by accumulations of coarse woody debris (as in fuel model 10) cause incident laser radiation to be scattered in the fuel bed

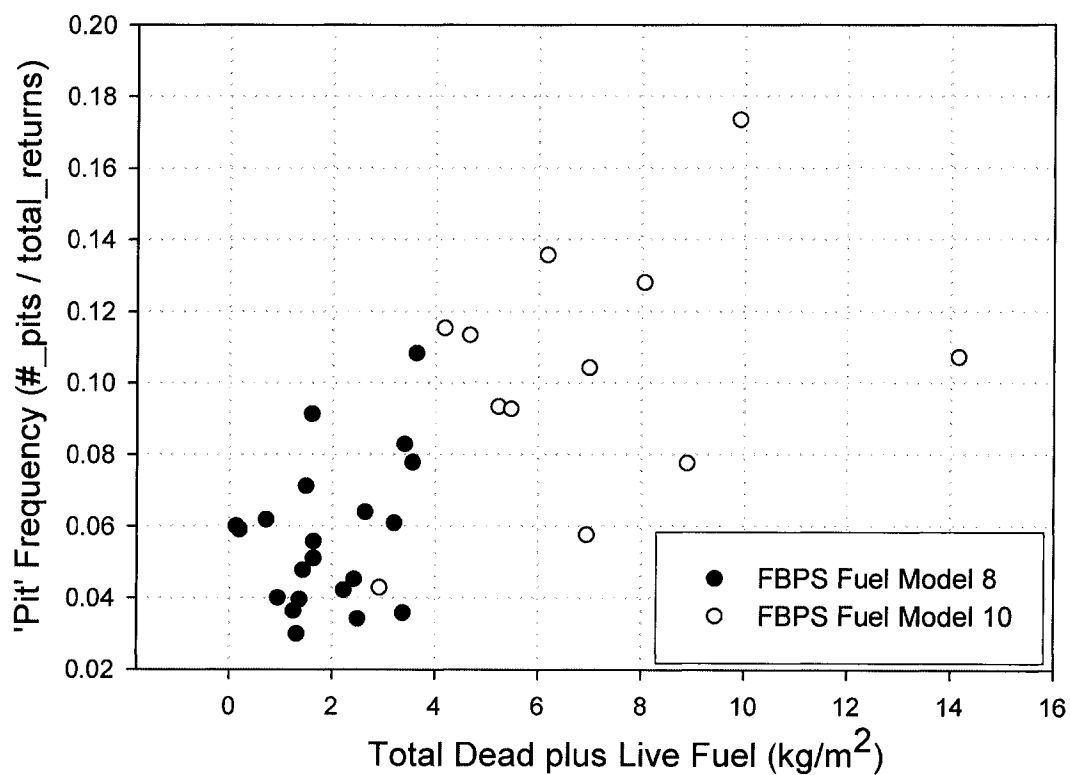


Fig. 7. The occurrence of ‘pitting’ is, in part, a function of live and dead biomass in the fuel bed.

Plots with sparse fuel (fuel model 8) show little tendency for this phenomenon, but pitting increases as surface fuel loads rise (fuel model 10).

but ultimately reflected to the receiver optics with sufficient strength to trip the receiver. The result is an apparent delay in return signal that causes an occasional reflection to appear below ground. These delayed returns occur more frequently, but not entirely predictably, in fuel beds characterized by large fuel volumes.

The implications of this finding are significant. First, it appears likely that roughness metrics like obstacle density do not necessarily relate directly to real, observable fuel characteristics, but rather that complex fuel beds cause scattering of the incident laser radiation (multipath) such that the apparent ground surface appears highly variable. It may not be discreet fuels entities that are being measured with laser altimetry, then. Instead, we could be characterizing the complexity of a reflective environment provided by the fuel bed, which is in turn correlated with quantifiable fuels properties. By this, I mean that if one went into the field and attempted to locate individual pieces of fuel that were identified by laser altimetry, he would not often find the entities in question. These results support the evidence from the previous discussion of live biomass that the quantity of coarse woody debris (and by association, anything in the fuel bed that presents ‘hard target’) drives the estimation of surface roughness by causing variations in the ground/near ground domain. They also explain, in part, why surface roughness does not correlate to some other fuels variables like fuel bed depth ($R^2 = 0.12$), integrated depth ($R^2 = 0.22$), and quadratic mean depth ($R^2 = 0.10$).

Although results from these latter variables have not been graphically presented due to their lack of significance, it is worth noting that none of the roughness metrics, or surrogates like mean obstacle height, are useful for predicting fuel depths. Mean obstacle height is probably not effective as a discriminator of surface fuel attributes primarily because heavily fueled areas exhibit a large number of points very near the ground that reduce mean obstacle heights for these plots. Secondly, the consistency of field depth measurements is questionable, given the subjectivity of ocular estimates on these most-difficult-to-measure entities.

Discussion and conclusions

Laser altimetry-derived fuel bed roughness is related closely to a suite of fuel characteristics, and is useful for estimating fuel volume and surface area at the Tenderfoot Creek Experimental Forest. The observed relationships between roughness and volume/surface area appear to be driven by the coarse woody debris in the fuel bed and not by the live biomass or the smaller dead fuels (i.e. ≤ 7.62 cm diameter). Obstacle density, standard deviation of GHD, and kurtosis of GHD each provide robust predictive power for 1000-hr and total fuel loads. OD performs slightly better at high fuel loads and δ GHD at low loads although the differences between models are small. Further, it appears that surface roughness as measured by laser altimetry does not depict discrete fuel entities, but rather that woody debris causes scattering of the incident laser radiation (multipath) such that the apparent ground surface of heavily loaded plots is highly variable relative to those with less fuel accumulation.

These results demonstrate that laser altimetry can be used to characterize fuel beds below closed canopies in lodgepole-type forests. A growing body of research relating laser altimetry to canopy characteristics (e.g. Magnussen and Boudewyn 1998; Magnussen et al. 1999; Naesset and Bjerknes 2001;) indicates that crown fuel parameters like canopy spacing, canopy bulk density, and canopy base height will soon be obtainable. In aggregate, these works point to laser altimetry as a valuable new tool for addressing many of the fuels mapping concerns that currently dominate the U.S. natural resource management agenda.

The research presented here is not intended to suggest that obstacle density, standard deviation of ground height distribution, or kurtosis of GHD are the best surface roughness metrics, and I anticipate that the future might bring better, more efficient ways to characterize fuel beds using laser altimetry. The intent has been to determine whether this technology is useful for deriving forest-floor attributes beneath closed canopies. Given the potential errors in field measurement of fuels using a limited number of line transects, the results presented herein

are a remarkable step toward fulfillment of this goal. Laser altimetry provides surface fuel estimates that are within the performance envelope of field measurements, and appears capable of filling the growing gap between the needs of those concerned with fire behavior and those concerned with fire effects by providing accurate estimates of the coarse woody debris that affects smoke production, duff consumption, soil exposure, and heat transfer to the soil.

It is worth noting that the reductionist approach adopted here may oversimplify expectations for statistics like the r^2 . Fuel beds are complex even within plots, and it is difficult to characterize individual components of a fuel assemblage, particularly given the lack of consensus on which components of the fuel bed are most important. For this reason, reducing fuel beds into components may not be in the best interests of land management in the long term. Rather, a holistic treatment of fuel beds may better and more efficiently serve management needs by providing fuels data that serve a broader range of applications, lend themselves to landscape-level management activities, that are adaptable to unanticipated future needs, and are cost effective. Although these issues will ultimately be resolved by user needs, they require consideration now as new fuels mapping technologies are being developed.

In addition to the above considerations, then, there are a number of other unanswered questions and issues pertaining to the application presented here. First, it is not yet clear how the results of plot-level comparisons will scale to fuel landscapes. Significantly, the size of map units and the thresholds that delineate one fuel type from another are as yet unidentified. Further, landscape-level fuels mapping may first require development of automated canopy-ground separation procedures that are more effective than those currently available. Second, it is not clear if the results presented here apply to forest types like Ponderosa pine (*Pinus ponderosa* P. & C. Lawson). In the Rocky Mountains of the United States, Ponderosa pine is perhaps the most significant forest type with regard to fire and fuels treatments because it is characterized by relatively short fire return intervals that in theory, make it particularly susceptible to the effects of

fire exclusion, and because it makes up a significant fraction of the wildland-urban interface. Third, efficiencies must be gained in data acquisition and processing to offset the prohibitive costs currently associated with laser altimetry data. Initially, these efficiencies will be gained through optimization of data collection protocols (scan width, flying height, ground speed) and through development of data processing tools. The effects of scan angle, beam intensity, and post-spacing on surface fuels characterizations are implicit in this discussion, and merit thorough investigation.

Given the above issues, it is clear that laser altimetry is still a research tool, recognizing that we are much closer to being able to utilize this tool for operational fuels mapping than we were even a few months ago. As the fire community awaits further development of laser altimetry-based fuels mapping technology, potential users must challenge themselves to reassess their fuels data needs. Laser altimetry is still costly and is difficult and time-consuming to process, but these barriers are falling quickly and fire managers should be prepared to describe specific data requirements and to speak to issues like map units and accuracy standards that are necessarily driven by user goals. Although fuels maps are a stated need of most administrative units on forested lands in the United States, it is my experience that this need has not often been evaluated carefully in the context of the models that will require fuels data, the purpose of using these models, and the time, effort, and cost of various data collection schemes. In short, fire managers must systematically address why they need fuels data, what they will use them for, and how much they are willing to commit to obtain them. The answers to these questions will dictate the prerequisite level of engagement in terms of cost, technology, and expertise required to map fuels efficiently. In many cases, photo series, field scouting, and aerial photography will still be the most reasonable approach to fuels mapping. However, laser altimetry will be a tool of choice when a high level of detail is required to meet very specific objectives on some fraction of our forested lands.

Acknowledgements

This research was supported by NASA through funding of project AFRR-000-0175 and by the USDA Forest Service Rocky Mountain Research Station through RJVA 00-JV-112220-48-018. This author wishes to thank the Tenderfoot Creek Experimental Forest and the Lewis and Clark National Forest for logistical support. Thanks also to the USDA Forest Service Fire Sciences Laboratory in Missoula for collection of fuels data.

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CHAPTER 4

MAPPING SURFACE FUELS WITH AIRBORNE LASER ALTIMETRY

Abstract: Observed relationships between airborne laser altimetry-derived surface roughness and field estimates of 1000-hr fuels allow coarse woody debris loads to be estimated accurately and mapped effectively in lodgepole pine-type (*Pinus contorta* Dougl. ex Loud) forests of west-central Montana. Comparisons of mapped fuels with both plot-level and area-based field estimates demonstrate that this form of remote sensing is useful for consistent characterization of the spatial distribution of fuel accumulations and their within- and between-patch variability. However, laser altimetry appears unable to assist in discrimination of rough surfaces caused by the presence of coarse woody debris and those caused by geomorphic roughness or rock debris. The resulting maps of coarse woody debris are spatially consistent with independently-derived photomorphic units from high spatial resolution optical imagery and with fire history. Specifically, regions characterized by heavy fuel accumulations correspond with texturally rough canopies and the occurrence of single fires that burned at least 250 years ago. In regions with lighter fuel loads and more complex fire histories, these relationships are not as evident, lending credibility to the notion that laser altimetry-derived fuel maps might be useful aids for documenting fire history in mixed-severity fire regimes characterized by episodes of frequent fire activity. The ability of the technology to provide consistent, fine-grained fuels data across broad geographic areas is evident, and in the context of the cost, time, and energy associated with mapping surface fuels, it reemphasizes the importance of clearly defining one's data requirements.

Introduction

While it is difficult to argue against the long-term success of fire incident management in suppressing wildfires, it is equally difficult to argue that existing firefighting efforts do not require adaptations to meet the growing challenges of increasingly complex incidents that unfold each summer under intense public scrutiny. Certainly, the persistence of drought across much of North America and the expansion of the urban interface into wildfire-prone areas have raised public expectations that firefighting efforts be both efficient and effective. Additionally, the trend of increasingly ambitious fire-use treatment objectives often conflicts with the risks associated with deliberately introducing fire to the landscape. Although prescribed fire is an effective tool for reducing hazardous fuels and restoring fire dependent ecosystems in which fire has been excluded, it is only an option when risk of damage to human, cultural, and natural resources is minimized (Kilgore and Heinselman, 1990).

As wildland fire management becomes more demanding and complex, it is becoming increasingly difficult for fire managers to work from experience alone. New tools that advance timely generation of map products that depict fire perimeters, fuels, and weather, among other things, have potential to improve the efficiency and effectiveness of both fire suppression and fire use. Accurate, spatially-explicit fuels maps are one of the most critical elements for planning and implementing fire activities, yet are arguably the most difficult to obtain. Of the three elements of the fire triangle, a fundamental principle linking weather, fuels, and topography, fuels are perhaps the most difficult to describe because they do not possess easily measurable intrinsic, definitive, qualities. Although in concept, any material that will sustain and propagate fire is fuel, the ability of a material to do so is largely governed by a suite of dynamic environmental factors. Consequently, the fuels landscape is constantly changing over time and space without any apparent change to its physical structure. A clear definition of fuels is further confounded by the adoption of diverse perspectives of fuels by fire personnel. For example, a fire behavior analyst

may prefer to define fuels as the materials directly contributing to fire spread, while a fire ecologist might limit a definition of fuels to the coarse woody debris that burn after passage of a fire front.

Additionally, the issues of scale that complicate characterizations of many spatial phenomena also plague quantification of fuels. Fire interacts with fuels, topography and weather at a variety of spatial scales (Miller and Urban, 1999), resulting in widely heterogeneous landscapes. The scale of heterogeneity is often different for ground, surface, and crown fuels such that it becomes difficult to consistently describe a fuels complex for a specified unit of ground. For example, coarse woody debris may exhibit a fairly small-grained variation, while grasses or duff form large patches of continuous fuels. At issue is whether a map of one specific fuel variable is spatially consistent with maps of other fuel variables. In many cases, this is probably not the case (i.e., it is unlikely that a stand map derived from airphoto interpretation is intrinsically related to the underlying distribution of surface and ground fuels, although it may characterize aspects of crown fuels quite well).

From the outset, then, it is important to recognize that there is significant disagreement surrounding the relative importance of various fuel attributes, the spatial scales at which they should be mapped, the required accuracy of resultant fuel maps, and the costs/benefits of mapping. Therefore, it should not be surprising that federal and state land management agencies do not possess accurate fuels maps for many land areas, nor have they developed interagency standards for systematic collection of such data. Yet fire managers are increasingly required to maintain a detailed knowledge of the spatial distribution of fuels on their units in order to write prescriptions, plan suppression tactics, predict fire behavior and smoke production, and estimate fire effects.

Certainly, many of the most useful measures of fuels are specific to the application for which they are being measured. At large scales, fuels variables such as tree-spacing, duff depth,

and distribution of coarse woody debris may be more important than smaller-scale variables of patch size and shape, and spatial pattern (Lertzman et al., 1998). The fire ecologist, then, takes a different perspective for burn plan-scale estimates of fire-related mortality and smoke production than for Columbia River Basin-scale estimates of fire severity. With this understanding, the problem of mapping fuels using laser altimetry is approached by selecting a single fuel attribute (1000-hr fuel load) with a demonstrated relationship to laser-derived surface roughness (Seielstad and Queen, in review), mapping it at a very fine grain, and evaluating its meaning in a spatial context. The above considerations of definition and scale are not addressed in this work directly. Instead, the results of this investigation are placed in the context of the spatio-temporal complexity of the fuels environment.

A stated goal of the proposed research, then, is to demonstrate that laser altimetry can be used to map surface fuels beneath closed-canopied Western conifer forests. A reductionist approach was adopted in previous work (Seielstad and Queen, 2003; Seielstad and Queen, in review) to describe plot-level relationships between laser altimetry-derived surface roughness and fuel attributes. In this project, these relationships are exploited to derive a surface fuel map for two sub-watersheds at Tenderfoot Creek Experimental Forest, Montana, whose spatial integrity and meaning can be evaluated through comparison with the attributes of independent representations of landscape pattern.

Approach

Chapters two and three have shown that laser altimetry-derived measures of surface roughness can be used to estimate fuel attributes on 0.10 acre plots beneath closed-canopied lodgepole pine (*Pinus contorta* Dougl. ex Loud) forests in west-central Montana. Obstacle density, standard deviation of the ground-height distribution (GHD), and kurtosis of the GHD each correlated highly with field estimates of fuel load, volume, and surface area, and the

observed relationships were driven primarily by coarse woody debris in the fuel bed and not by live biomass or smaller dead fuels.

Here, I build on the previous research to map fuels in Spring Park Creek and Sun Creek, two sub-watersheds of Tenderfoot Creek, a tributary of the Smith River. Specifically, a single roughness metric, standard deviation of GHD, is used to predict 1000-hr fuel loads (> 3-inch diameter pieces) for a continuous 1850-acre (749 ha) block of forest beneath seven flightlines of high-density, near-nadir, laser altimetry data. The goal is to explore the surface fuel mapping potential and efficiency of laser altimetry by creating a map, ground-truthing it, and comparing it with independent characterizations of spatial pattern at Tenderfoot Creek Experimental Forest. Because each of the roughness metrics provided similar predictive power (Seielstad and Queen, in review), the easiest to calculate was selected (standard deviation of GHD), and the fuel variable (1000-hr fuel load) that contributed most to surface roughness was chosen.

Separation of canopy points from ground/near ground points became a significant consideration when applying fuel load calculations from the plot-level to the landscape. In the plot-level work, canopy was separated from ground manually because existing automated separation techniques inadvertently considered as ground returns many points within the fuel bed (Huising and Pereira, 1998; Wehr and Lohr, 1999). For fuels *mapping* work, a digital elevation model (DEM) was created from a vendor-provided bare-ground data set generated by proprietary methods undisclosed to this author (an unfortunate side-effect of working with commercial data).

In general, development of a bare ground DEM is a two-step process that is required to provide a datum from which vegetation heights are measured. First, the vegetation must be removed from the surface, and second, the ground returns must be interpolated. Vegetation is typically removed based on statistical analysis of height values within a moving window, using morphologic and/or edge detection filters (Huising and Pereira, 1998). For example, a general terrain model can be generated through extraction of the lowest returns in a moving window. A

second filter is then passed across the retained points to remove additional postings with a height difference exceeding a given threshold. This step is repeated several times with an increasingly small window until an acceptably smooth surface is produced (Petzold et al., 1999). The final output is a function of window size and height thresholds, suggesting that selected parameters should be consistent with observable terrain morphology. Kraus and Pfeifer (1998) determined that the most accurate DEMs are obtained using a semi-automated approach like the one suggested above and adjusting the model manually using landmarks like open fields and bare ground.

Although the specific methods used by the vendor to extract bare-ground points are unknown, I believe that only a rough approximation of the ground surface might be necessary to provide meaningful estimates of surface fuel attributes. This belief differs from an earlier assumption (Seielstad and Queen, 2003) that effective fuel estimates might only be obtained with a precise bare-ground DEM. These authors showed that laser altimetry-derived surface roughness does not depict discrete fuel entities, but rather that heavily loaded plots with accumulations of 'hard targets' appear highly variable due to multipath effects characteristic of complex reflective environments. Further, the calculation of standard deviation of GHD is tolerant of some variation in the derived ground surface as long as estimated ground surface approximates reality. I suggest that an iterative filtering algorithm based on minimum heights will eventually select the lowest points in the data set and that the subsequent ground surface derived from these points will usually be at or below the actual ground surface and rarely above it. Because only points on the ground and within the fuel bed (< 2 m in height) are evaluated for derivation of surface roughness, a potential consequence of this phenomenon is the inadvertent truncation of the top of the fuel bed when the estimated ground surface is below the actual ground surface. This might result in smoother than expected surface roughness values for some heavily

loaded plots. The converse of this condition is probably never true given the arguments presented above.

Recognizing the possible limitations of the vendor-provided bare ground extraction, then, a 1000-hr fuel surface was generated for the Spring Park and Sun Creek sub-watersheds, fuel estimates were compared with field measurements obtained at two types of field plots, and the fuel map was compared to independently-derived photomorphic units and fire history data. The former comparison is intended to substantiate the validity of the fuels estimates and the latter comparison begins to place laser altimetry-derived fuel distributions in a spatially meaningful context.

Material and methods

Study site

Surface fuels were mapped using laser altimetry data within the Spring Park and Sun Creek drainages, two sub-watersheds of Tenderfoot Creek. These watersheds form the basis for a series of studies designed to test the ecological response of lodgepole pine forests to a variety of management treatments. Each sub-watershed is paired with an adjacent hydrologically similar watershed, and hosts both mechanical and prescribed fire treatments. The Spring Creek sub-watershed is 1032 acres in size on which 376 acres have been treated, and the Sun Creek sub-watershed covers 859 acres with 389 acres of treatment (McCaughey, 1998). Both sub-watersheds contain a mix of lodgepole pine interspersed with older stands of subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.) and Engelman spruce (*Picea engelmannii* Parry ex Engelm.). Vegetation patterns reflect a complex fire history (Barrett, 1993) characterized by a series of mixed-intensity fires for which there is evidence dating from 1580 onward.

The Tenderfoot Creek Experimental Forest, which hosts this study, is a 9125 acre (3693 ha) study area lying at 2100 meters elevation in the western Little Belt Mountains of west-central

Montana. It was established in 1961 as a testbed for development of management techniques that promote harvesting of lodgepole pine while maintaining soil stability. In this capacity, the U.S.F.S. Rocky Mountain Research Station Northern Rockies Forest Ecosystem Research Unit and the Lewis and Clark National Forest have partnered to advance these goals. It is an excellent laboratory in which to test new fuel mapping methodologies because it spans a broad range of possible conditions for closed-canopied Western conifer forests and is topographically diverse. Fuel loadings range from 0.1 to 14 kg/m² with a variety of stand structure and regeneration patterns. However, it is not so diverse as to unnecessarily complicate evaluation of a new remote sensing application like the one presented here.

Field data acquisition

The fuels data used to validate laser altimeter-based estimates of fuel load were collected in two phases. The first data set was derived using the line-intercept method (Brown, 1970; 1974) at gridded fixed-area plots in 1997/1998 following ECODATA protocols (Jensen et al., 1993). Fuels data were collected along five transects per plot, each transect offset by 60 degrees from the previous transect in order to reduce bias caused by non-random fuel distribution and piece orientation. The second data set was obtained at a spatially dense distribution of sub-plots located within the proposed treatment areas of Spring Park Creek. Brown's (1974) line-intercept method was employed on two transects per sub-plot, each oriented at right angles to its partner transect. These data were aggregated according to treatment units resulting in area-based mean fuel load and variance estimates for each unit and for sub-units with unique fuel characteristics.

Airborne laser data acquisition

Laser altimetry data were obtained for the Spring Park and Sun Creek watersheds on October 10-13, 1999 with an Aeroscan laser ranging system subcontracted by Spencer Gross

Engineering, Inc. Seven flightlines of data were used in this study, each with a swath width of 240 meters. Up to five echoes per pulse were recorded resulting in an average return density of 1.5 returns per square meter. Nominal footprint size was 0.90 meters. The laser pulsed radiation at a wavelength of 1064 nm at 15 kHz, scanning across track to collect a sinusoidal pattern of points along each flightline. The laser, inertial measurement unit, and GPS data were correlated using GPS time and processed by Spencer Gross Engineering, Inc. to produce a point file of x,y,z on the UTM projection (Zone 12, NAD83). Comparisons of data between flightlines and against a kinematic survey of paved roadways near the study area resulted in estimated horizontal accuracy of 1.8 meters and vertical accuracy of 15.5 cm RMSE.

Data processing

Seven adjacent flightlines of raw laser altimetry data were merged into a single dataset and differenced from a bare ground digital elevation model (DEM) to normalize by height above ground. The DEM was created by calculating a mean ground surface with an 8 x 8 meter rectangular moving window on the ground return dataset. All points within the fuel bed (< 2 meters in height) were extracted, and a 0.10 acre circular filter was passed across the data to create a standard deviation surface gridded at one meter. The size and shape of the filter matched the size and shape of the plot-level comparison to provide internal consistency. Finally, the calculated standard deviation values were input into a linear model derived from observed plot-level surface roughness-fuel attribute relationships (Seielstad and Queen, in review) to generate a 1000-hr fuel surface for the study area.

In order to facilitate objective comparisons with fire history polygons derived by Barrett (1993), the fuels data were clustered using the Iterative Self-Organizing Data Analysis Technique (ISODATA) (Tou and Gonzalez, 1974). This analysis was performed to group the landscape into patches with relatively homogenous fuel characteristics. ISODATA requires the user to specify a

maximum number of clusters (N), which are used to determine N arbitrary cluster means. The algorithm then assigns pixels to each cluster based on spectral distance, repeating iteratively and recalculating cluster statistics at each iteration until a user-defined convergence threshold (T) or a fixed maximum number of iterations (M) is reached. The convergence threshold refers to the maximum number of pixels allowed to remain in their respective classes with each iteration.

Initially, the fuels data were clustered with $N = 3, 5, 10, 15$, and 20 , $T = 0.95$, and $M = 6$. Each of the runs reached its convergence threshold in four iterations. At $N = 3$ and 5 , the fuels data spatially clumped into two general units; those characterized by large fuel loads and those characterized by small fuel loads. These units corresponded visually with some of Barrett's (1993) fire history polygons. At $N = 10, 15$, and 20 , the fuels data spatially clumped into three general units; relatively homogenous regions associated with large and small fuel loads, and 'salt-and-pepper' regions characterized by spatially variable fuel loads. Again, these regions corresponded visually with some of Barrett's (1993) polygons. The convergence threshold (T) remained unchanged for all runs because the value (0.95) resulted in efficient classification with the desired outcome of aggregating fuels into contextually meaningful patches (i.e., Barrett's fire history).

Subjectively, clustering with a larger number of classes ($N = 10, 15, 20$) more completely reflected Barrett's fire history than clustering with smaller numbers of classes ($N = 3, 5$). Further, information content at $N = 10, 15$, and 20 was redundant. Therefore, the thematic layer derived using 10 classes was chosen for additional processing. It is important to acknowledge that although the classifications themselves objectively organize the fuels data, selection of classification parameters introduces an element of subjectivity, particularly with a priori knowledge of fuels distributions and fire history at Tenderfoot.

At this point, the goal became to clump contiguous regions. There were three general classes loosely grouped throughout the scene; heavy fuel load regions, light fuel load regions, and

mixed regions. The former two classes were in large part already clumped, with small interior islands and ragged edges. The mixed regions were ‘salt-and-peppered’ with patches of high and low fuel load ranging in size from 0.10 to 1.0 acres.

Initially, a circular 0.10-acre density filter was applied to the 10-class thematic layer. This filter identifies the number of pixels within the neighborhood that have the same value as the center pixel. If more than half of the pixels in a window matched the center pixel value, that pixel was recoded to match the dominant value; otherwise, there was no action. The size of the filter provides consistency with the reductionist approach adopted in chapters 2 and 3, and produces as fine-grained data as is reasonable given previous work. This filter was reapplied to the thematic layer six times, resulting in relatively homogenous regions characterized by high or low fuel loads. The mixed regions remained unchanged. The size and shape of the resulting patches remained unchanged at more than six iterations, indicating no benefit from further attempts at smoothing by this method.

One outcome of application of the density filter was that each homogenous region was encircled by an annulus of ‘transitional’ class values, values that were unaffected by filtering. This effect was resolved by applying ‘region growing’ tools, which are readily available in most digital image processing software packages. The specific tool adopted in this analysis (ERDAS Imagine 8.5) allows the user to select a seed pixel and to grow a region outward from this pixel, incorporating all contiguous pixels within a user-specified spectral distance from the initial pixel. This process allowed effective recoding of the transitional class values surrounding each homogenous region and removed remaining islands from these regions. The result was class homogeneity within all regions except those characterized by clumpy, highly variable distributions of fuel loads (the aforementioned mixed regions). These remaining mixed regions were masked and recoded, resulting in a thematic layer with unique class values representing each ‘fuel-morphic’ unit. Finally, the region growing tools were reapplied to non-forested areas

(rocky debris fields, grassy meadows) in the raw fuel load image to create a non-forest mask that was applied to the fuel-morphic unit map. Non-forest regions were identified visually from 1-meter spatial resolution IKONOS panchromatic imagery.

Results and discussion

Fuel map integrity

The legitimacy of the laser altimetry-derived fuels map was evaluated in two ways. First, estimated 1000-hr fuel loads were compared with field measurements at fifty-four 0.10-acre ECODATA plots (Fig. 1). Thirty of these plots were used in the plot-level analysis described in chapter 3, resulting in an evaluation that is useful for assessing consistency with plot-level results. Second, estimated mean 1000-hr fuel loads were compared with observed mean fuel loads within treatment units in the Spring Park Creek sub-watershed (Fig. 1). This latter areal comparison independently substantiates the validity of the observed relationships between laser altimetry-derived fuel loads and field measurements of fuel loads. The goal of these comparisons was to evaluate the hypothesis that laser altimetry-derived surface roughness continues to provide reasonable estimates of 1000-hr fuel loads that are consistent with estimates provided by the line intercept method. Further, given previous uncertainties regarding the accuracy of field estimates by the line intercept method (Seielstad and Queen, in review), it was more important that the resultant fuels map be spatially meaningful in the context of fuels at Tenderfoot than in perfect agreement with field estimates (i.e., the fuels map should generally depict differences in fuel accumulation that reflect patterns in field observation, but not necessarily match, one-for-one, the field estimates).

Laser Altimetry-Derived 1000-hr Fuel Load

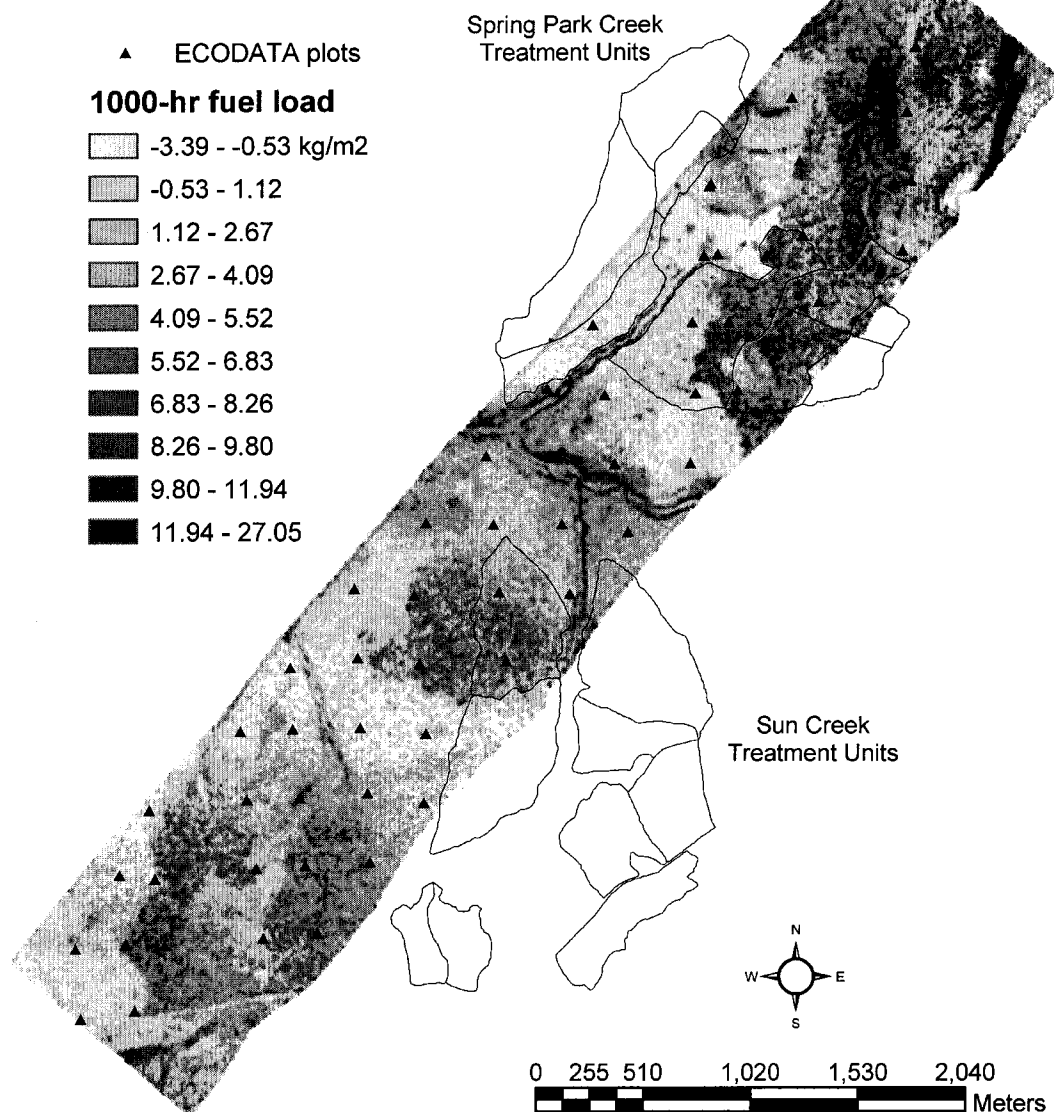


Fig. 1. Fuel load map based on laser altimeter-derived surface roughness. Locations of 0.10-acre ECODEATA plots used in the analysis are depicted as black triangles. Treatment units are shown for both sub-watersheds (only the Spring Park units used in analysis- no data for Sun Creek). Roads are visible in the southeast of the imagery and along north-south borders of the Spring Park units. Heavy fuel accumulations, rocky debris, and drainage networks appear as dark patches.

Figure 2 shows the relationship between laser altimetry-derived 1000-hr fuel load and field-measured 1000-hr fuel load at the ECODATA plots within the Spring Park and Sun Creek sub-watersheds. The graphic clearly demonstrates that laser altimetry provides reasonable estimates of fuel load, particularly above 2 kg/m^2 . As was noted previously, many of the plots used in generation of the model relating standard deviation of ground height distribution (GHD) to fuel load are included in this analysis (open circles in Fig. 2). These plots were initially selected because they were located at, or near the center of fuel ‘stands’ (Seielstad and Queen, in review) and because they spanned the range of fuels variability observed at Tenderfoot Creek. The remaining plots (filled circles in Fig. 2) are characterized by relatively light fuel loads and are located on ‘edges’ where fuel attributes change quickly across short distances. The observed variability associated with these plots (and, in fact with all lightly loaded plots) in figure 2 is not unexpected given the findings of Pickford and Hazard (1978) and Lutes (1999) among others that very long transects are necessary to provide accurate load estimates in lightly loaded fuel beds.

In sum, the standard deviation-fuel load model performs adequately except at very low fuel loads and is consistent with model output from the plot-level comparisons. However, the presence of negative predicted values suggests flaws in the model; not necessarily unexpected given that mapped values were obtained using a different canopy-ground separation than the one used in the plot-level study, and recognizing that the observed relationship is affected by the same plots that were used in generation of the model. Regardless, we might still conclude that the mapped 1000-hr fuel loads are consistent with fuel loads estimated at the ECODATA plots.

Within the treatment units of Spring Park Creek, laser altimetry-derived mean 1000-hr fuel loads are also highly correlated with predicted mean fuel loads (Fig. 3). It is not clear if the relationship is linear or exponential ($e^{x/2}$) with the paucity of points between one and three kg/m^2

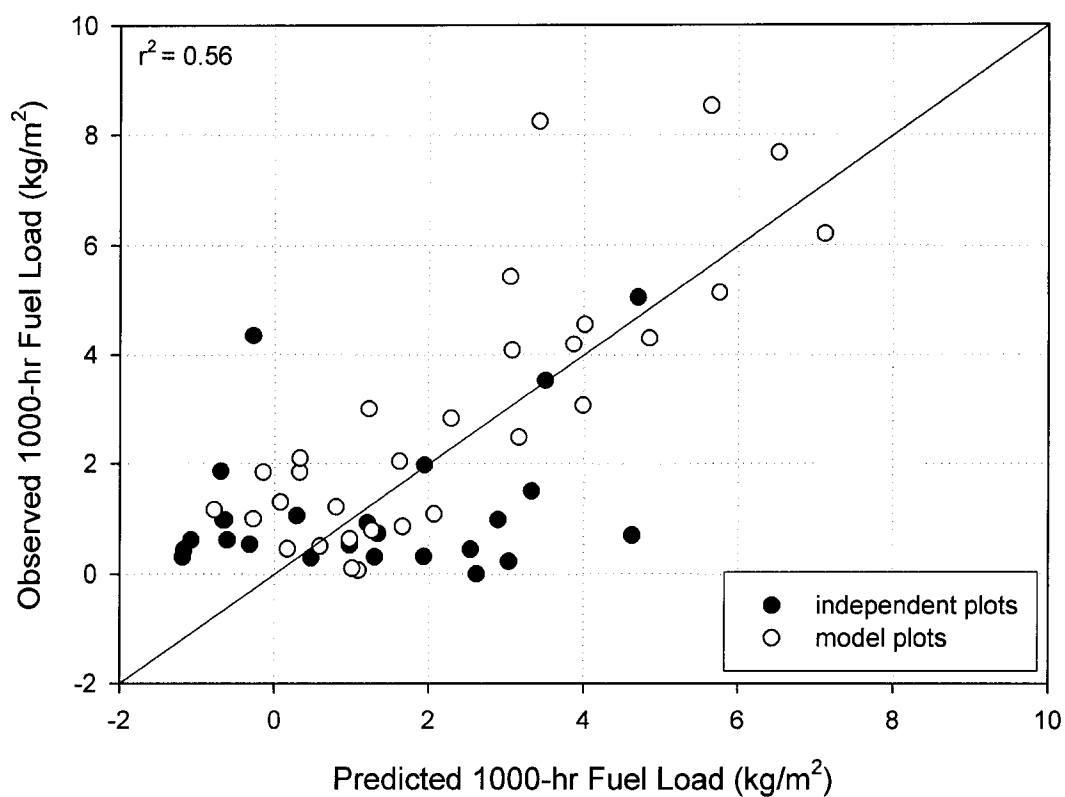


Fig. 2. Observed versus predicted 1000-hr fuel load for 0.10-acre ECODATA plots within the Spring Park Creek and Sun Creek sub-watersheds. Open circles show plots used in generation of the linear model relating standard deviation of the ground height distribution (GHD) to 1000-hr fuel load (Chapter 3). Filled circles were not used in the model. 1:1 line depicted.

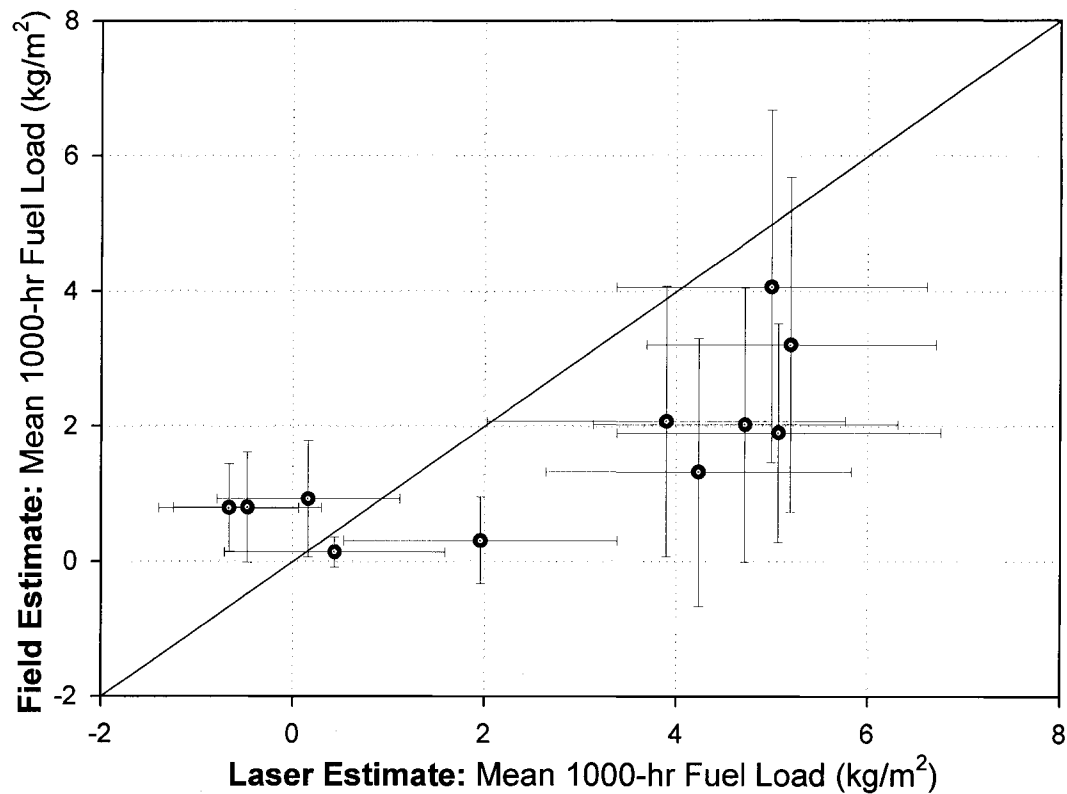


Fig. 3. Area-based laser estimates of mean 1000-hr fuel load are correlated with field estimates, but the laser data result in over-prediction of fuel loads at all points except those near 1 kg/m². It is not clear if the relationship is linear or exponential, but the 1:1 line is shown for reference. Error bars represent one standard deviation.

and above five kg/m². Given previous observed vs. predicted relationships one would suspect that it is linear, unless there are systematic, fuel-load dependent differences (i.e., skewness) in the histograms associated with each treatment unit. However, evaluation of mean, median, and mode fuel load for each unit shows that this is not the case. It does seem likely that fuel estimates based upon surface roughness would become asymptotic at very high loads when much of the fuel is obscured by debris at the top of a fuel bed. However, this phenomenon is probably not being depicted in figure 3 given that the plot-level comparisons described in chapter 3 were non-asymptotic up to 12 kg/m² and only one laser estimate in any of the Spring Creek treatment units exceeds this value.

In general, laser altimetry over-predicts field measurements of mean 1000-hr fuel load in the treatment units at all loadings except those near 1 kg/m². Further, variance based on altimetry data is larger than field variance at low loads and smaller at high loads (Fig. 4). It is worth noting that these observations are consistent with what one might intuitively expect. Recall that the mean and standard deviation of laser altimetry-derived fuel loads is calculated from entire treatment units, while statistics from field measurements are based on 6-40 samples per unit. In the lightly loaded stands of the Tenderfoot which are typically characterized by only occasional jackpots of fuel, one might expect a sampling scheme based on a small number of samples to most often miss these jackpots and consequently under-represent actual mean load and variability. In heavily loaded stands, which contain more variability than lightly loaded stands (Fig. 4), the opposite appears to be true. This may be partly a function of a mismatch between the spatial distribution of fuels in these stands and transect lengths. Pickford and Hazard (1978) clearly showed that estimated fuel population variance decreases as a function of increasing both transect length and total number of transects in heavily loaded stands, and closer investigation of the field data at Tenderfoot does reveal enormous variation in adjacent transects, particularly those in heavily loaded areas where estimates of 0 tons/acre from one transect and 28-56

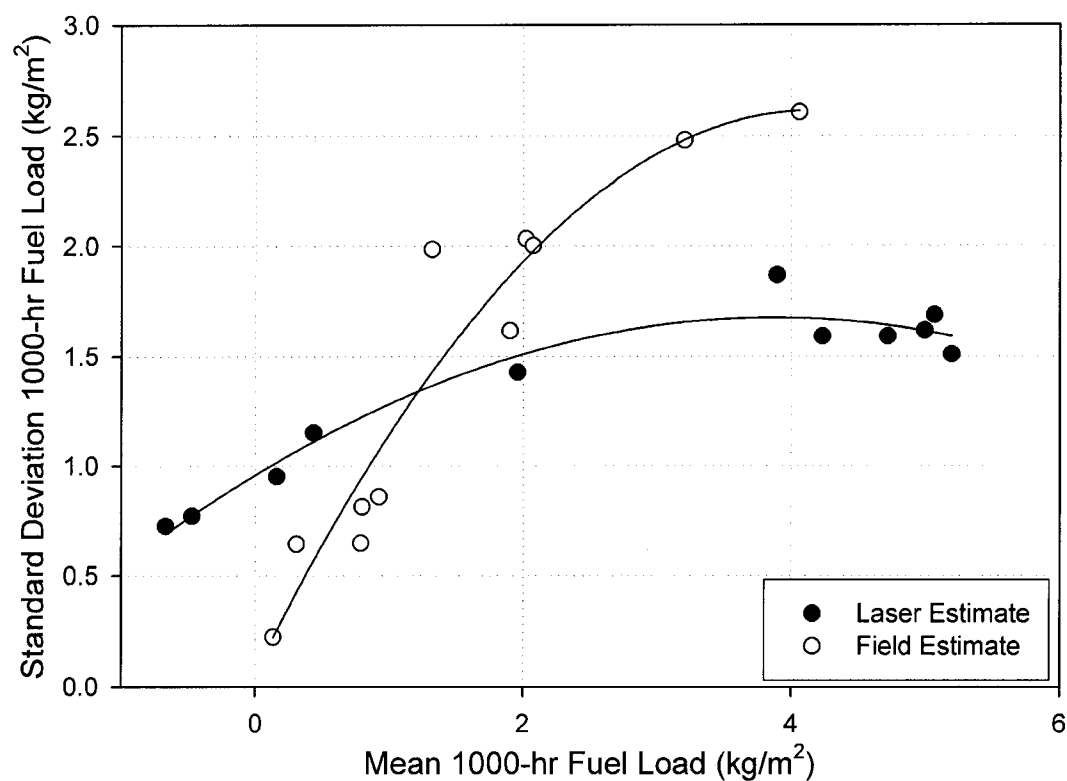


Fig. 4. Laser estimates of within-unit fuel load variance are larger than field estimates at low volumes but smaller at high fuel volumes. The two functions intersect near a mean fuel load of 1 kg/m², the same place in which laser estimates under-predict field estimates of mean fuel load (see figure 3).

tons/acre from its partner transect are common. I propose that estimated population variance is lower in heavily loaded stands in the laser data set because the entire population has been sampled for each. Although the inherent ‘smoothing-effect’ of the filters used to calculate surface roughness from the laser altimetry data may artificially reduce variance in the laser estimates of fuel load, the patterns observed in figure 4 are consistent with findings of Pickford and Hazard (1978).

There are a number of additional observations worth pointing out in this comparison. For example, the function relating standard deviation 1000-hr fuel load to mean 1000-hr load becomes asymptotic at high fuel loads with both field and laser estimates (Fig. 4), perhaps suggesting that there are load-dependent constraints on either load variance or on measurement techniques. It is not clear whether these conditions are specific to Tenderfoot or broadly pertain to other fuel types. Additionally, the standard deviation/mean fuel load functions for laser estimates and field estimates intersect at about 1 kg/m^2 (4.4 ton/acre), the same place at which laser estimates under-predict field estimates. It is conceivable that when fuels on lightly loaded plots reach some critical threshold ($\sim 1 \text{ kg/m}^2$?), one is more likely to field sample jackpots of fuel that result in over-prediction of mean fuel loads. It is not clear, however, what effect this proposed phenomenon might have on estimated unit variance, but it might serve to increase it.

In conclusion, laser altimetry-derived surface roughness provides 1000-hr fuel load estimates that are reasonably consistent with field estimates. Further, because the laser altimeter samples entire fuel populations within the study area, I am prone to trust its ability to characterize effectively the spatial variability of fuels within the two sub-watersheds more than the field estimates. As will become evident in the following discussion, the laser-based fuels map provides a spatially meaningful representation of 1000-hr fuels that would be difficult to duplicate with field observations. The core requirement of spatial consistency is clearly met with this dataset, and I suggest that it portrays fuel distributions at Tenderfoot more consistently than

field measurements. Future work should further substantiate the precision of laser and field estimates so that a one-for-one comparison is possible.

Fuel map characteristics

The laser altimetry-derived 1000-hr fuels map broadly agrees with a general impression of the study area (Fig. 5, left panel). Prominent features like Spring Park, the animal-cracker shaped meadow in the northwest portion of the study area, are clearly visible as a smooth open areas. Within this meadow are clumps of subalpine fir, also visible in the map. Roads are clearly apparent as relatively smooth surfaces, most noticeably around Spring Park and in southeast corner of the study area. The drainage pattern is reflected in ribbons of heavy fuel load; spatially accurate but probably incorrectly depicting the fuels. These narrow, deeply incised channels may appear rough to the laser altimeter because they contain significant outcroppings of rock and/or because micro-topography changes so abruptly across the channels that a bare ground surface is difficult to obtain accurately. Additional fieldwork should substantiate these hypotheses and will verify whether the drainages actually contain significant coarse woody debris. They are characterized by relatively large apparent fuel loads and exhibit the most variance of any of the features in the study area (mean fuel load: 6.777 kg/m^2 ; std dev: 2.581 kg/m^2).

In non-forested areas along Tenderfoot Creek itself and in the very northern and southern portions of the study area, rock outcrops and debris fields provide very rough reflective surfaces that without support of optical data, would also appear to be heavily loaded stands. These areas exhibit the roughest surfaces in the Tenderfoot, characterized by apparent 'fuel loads' of up to 19 kg/m^2 (minimum: 4.336 kg/m^2 ; maximum: 19.121 kg/m^2 ; mean: 9.694 kg/m^2 ; std dev: 1.675 kg/m^2). For comparison, the open meadows found at Tenderfoot in the mid-slope portion of the study area have very low apparent fuel loads (min: -2.459 kg/m^2 ; max: 0.603 kg/m^2 ; mean: -1.973

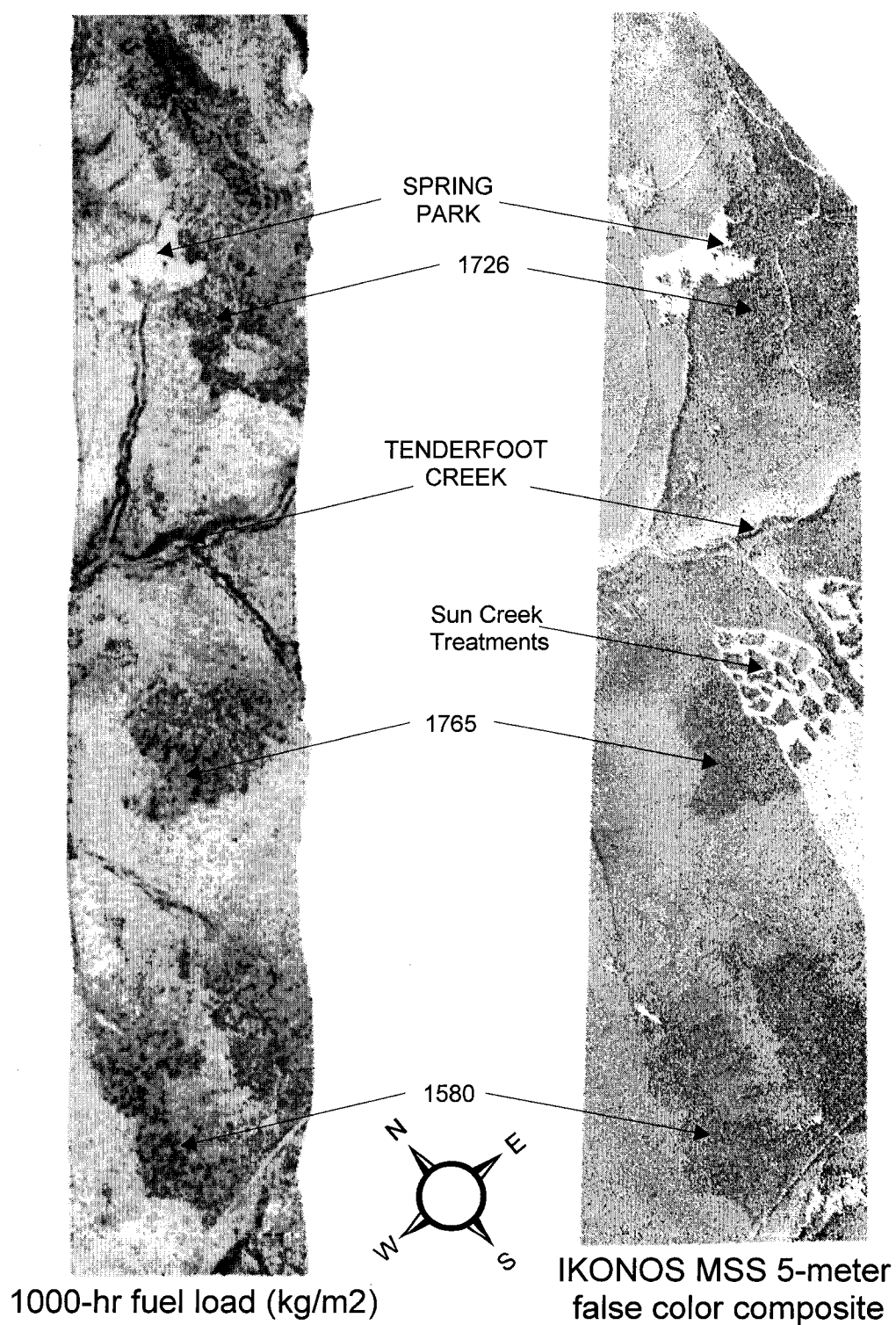


Fig. 5. Fuel load – canopy tone/texture comparison. On the left, dark tones represent heavy fuel loads and bright tones depict light loads. Treatments visible in right frame (crossing 1765 unit) were initiated after acquisition of the data in left frame. Significant fires (Barrett, 1993) identified in both frames.

kg/m²; std dev: 0.479 kg/m²). These observations highlight one of the initial suppositions that laser altimetry alone cannot easily be used to discriminate between fuels and geomorphic roughness. Consequently, accurate fuels maps based on laser altimetry will require ancillary data like optical imagery to help distinguish between fuels and other debris that produce rough surfaces. If the rough surfaces occur under tree canopies, however, we are faced with the same limitations imposed on current fuel mapping methods that rely on optical remote sensing.

The timbered landscape of Tenderfoot spans a range of 1000-hr fuel loads from none to 13.3 kg/m². Distributions are patchy with clumps of relatively homogenous fuels approximately 75-150 acres in size that generally correspond with several photomorphic features in optical imagery and with fire history polygons identified by Barrett (1993). Heavily loaded regions are typified by mean fuel loads of 5-8 kg/m² while lightly loaded regions contain 0.45 – 0.50 kg/m². Standard deviations range from 1.11-1.67 kg/m² in areas with heavy fuel accumulations to 0.43-0.88 kg/m² in areas with little fuel.

Fuel and photomorphic units

Qualitative visual comparison of the laser altimetry-derived 1000-hr fuels map with a high spatial resolution (5m) multispectral IKONOS image reveals linkages between photomorphic units and fuels distributions (Fig. 5). In general, the regions that correspond are characterized by heavy fuel loads, multi-strata canopies, and mixed species composition (e.g., lodgepole pine, Engelman spruce, subalpine fir). For the purposes of this discussion, these stands will be referred to following Barrett's (1993) fire history nomenclature as: the 1580 stand (bottom left); the 1873 stand (bottom right); the 1765 stand (center); and the 1726 stand (upper right). Additionally, the drainage network and non-forested areas stand out in both images. It is worth noting that the IKONOS image depicts some of the stand treatment activities in the Sun Creek sub-watershed that occurred after lidar data acquisition (center east of the study area). The

observed correspondence between images shows that canopy tone/texture is related to the fuels below the canopy in many parts of Tenderfoot and suggests that air-photo interpretation could be used with limited field sampling to create reasonably accurate fuels maps. More significantly, it implies that at least for stands not experiencing fire in the last 250+ years, canopy reflectance characteristics are linked to surface fuel attributes. This observation runs counter to a common assumption in optical remote sensing of fuels that canopy reflectance is not diagnostic of underlying fuel distributions (Keane et al., 1998). However, it makes sense at Tenderfoot when one considers these stands in the context of fire regime and time since last fire.

Let's consider the 1765 stand by way of example. There is ample evidence of a relatively large stand-replacing fire in 1765 at Tenderfoot (Barrett, 1993). However, the only remnant of this fire that has not burned again in subsequent years is the roughly circular region south of Tenderfoot Creek in the center of the study area. In this region, the 1765 fire probably removed surface fuel but left behind tons of standing dead fuel that, over time, was returned to the fuel bed. Following the fire, regeneration occurred (probably lodgepole, initially), the stand matured, and secondary regeneration (spruce, fir) took place. The result is a region with relatively unusual canopy architecture for Tenderfoot, in which canopy attributes are diagnostic of heavy fuel loads. In the remainder of area burned by the 1765 fire, additional fires have intermittently added and removed fuels, reset regeneration activities, resulted in development of multi-aged lodgepole stands, and effectively disconnected canopy attributes from surface fuels attributes. In these latter regions, it becomes difficult to assess surface fuels accurately from canopy tone and texture. In areas characterized by low and mixed-severity fires where the canopy is not always directly affected, then, there is a decoupling of surface fuels distributions and the canopy attributes which are observable by conventional optical remote sensing.

Laser altimetry, however, seems to provide reasonable estimates of fuel loads within regions characterized by multiple fires, and fuel *patches* are clearly evident in these areas. Laser

altimetry also portrays variability within the heavily loaded stands that is not readily apparent in the IKONOS imagery. Therefore, if one's goal is to characterize surface fuel distributions (and variability) for large areas like Tenderfoot at a very fine-grain, laser altimetry is a better tool than high-resolution optical imagery. However, if one wishes to delineate FBPS fuel model polygons generally, interpretation of aerial photographs is probably sufficient, at least where stand-replacing fire regimes are characteristic.

In summary, observed correspondence between laser altimetry-derived surface fuels and optically-derived canopy tone/texture can be explained, in part, by fire history and related fuel dynamics. However, a secondary explanation requires further discussion. It is possible, although unlikely, that the correspondence is a function of interaction between incident laser radiation and the canopy, and has little to do with surface fuels. In this scenario, different canopy architectures cause systematic patterns of displacement of individual laser returns downward into the fuel bed, resulting in artificially rough surfaces that coincidentally translate into high fuel loads. Previous research (Seielstad and Queen, in review) showed that negative noise, or pitting, occurs with greater frequency in heavily loaded fuel beds than in lightly loaded beds. A multipath effect was hypothesized to explain this phenomenon, whereby coarse woody debris in the fuel bed caused relatively coherent scattering of incident radiation such that radiation was returned to the receiving optics with sufficient strength to trip the receiver, but was fractionally delayed by scattering within the debris field. It is reasonable to assume that this same effect could occur in the lower canopy, and depending on canopy architecture, the resulting 'pits' might systematically fall within the fuel bed, thus independently influencing derivations of surface roughness. If this phenomenon is occurring at Tenderfoot, the observed laser altimetry-derived fuel distributions are actually a reflection of canopy architecture and are therefore only coincidentally related to actual surface fuel distributions. It is difficult to assess the likelihood of this scenario, but if true,

enthusiasm for the technology as a surface fuels mapping tool is dampened significantly.

However, the latter argument is rejected and the former accepted for the several reasons.

- (1) The previously described multipath effect appears to be a function of hard target in the fuel bed. Stands with significant understory but little coarse woody debris appear relatively smooth in terms of laser-based surface roughness (i.e., the regenerative understory is not causing the pitting observed in heavier loaded stands). Although possible, it seems unlikely, then, that live crown higher in the canopy is interacting differently with incident radiation than crown near the ground. Larger branch size associated with sub-canopy of the dominant trees could be advanced as a possible contributor to pitting, but evidence from within the fuel bed suggests that < 3 inch diameter pieces (i.e., most branch biomass) do not contribute significantly to laser altimetry-derived surface roughness.
- (2) Laser altimetry-derived measurements of surface roughness are linearly correlated with field estimates of 1000-hr fuels across the range of loads at Tenderfoot, irrespective of differences in canopy architecture. There is no discontinuity or offset in the observed relationships at higher fuel loads, even though all of the heaviest loaded plots are characterized by relatively complex, multi-storied lodgepole/spruce/fir canopies.
- (3) Lodgepole stands growing in the rocky debris fields near Tenderfoot Creek and in the very northern and southern portions of the study area have characteristically rough surfaces as depicted by laser altimetry. In adjacent, less rocky areas, these same stands exhibit smooth surfaces associated with light fuel accumulations. We might conclude

from this observation that at least in these stands, laser altimetry is actually characterizing surface roughness and not a canopy attribute.

- (4) A complex fire history documented by Barrett (1993) reveals that much of the Tenderfoot landscape is characterized by a series of mixed-severity fires, including several underburns that impacted the canopy minimally if at all. It stands to reason, then, that surface fuel distributions are largely disconnected from distributions of trees with similar canopy architecture for much of Tenderfoot. In fact, this is exactly what we observe in the fuels, fire history, and photomorphic unit data. The distribution of laser altimetry-derived 1000-hr fuel load corresponds with canopy attributes observable in high-resolution multi-spectral imagery only for heavily loaded stands with a history of single fires that occurred at least 250+ years ago. Elsewhere, there is significant disagreement between estimated fuels, observable patterns in the optical data, and in proposed fire history (discussed below). So although it is possible that canopy/laser interaction above the fuel beds of heavily loaded stands is contributing to surface roughness via a multipath effect, it is unlikely given the arguments presented above, and the phenomenon is definitely not occurring elsewhere in the study area.

Fuel and fire history

There is remarkable correspondence between laser altimetry-derived 1000-hr fuel load and Barrett's (1993) fire history at Tenderfoot Creek Experimental Forest (Fig. 6). In most cases, accumulations of heavy fuel loads closely match fire history units that have not experienced fire for long periods of time. Noteworthy are the 1580, 1765, and 1726 units (from southwest to northeast). The 1765/1873, 1873/1902, 1902/1873, 1845, 1726/1889, 1873/1676, and 1873/1921

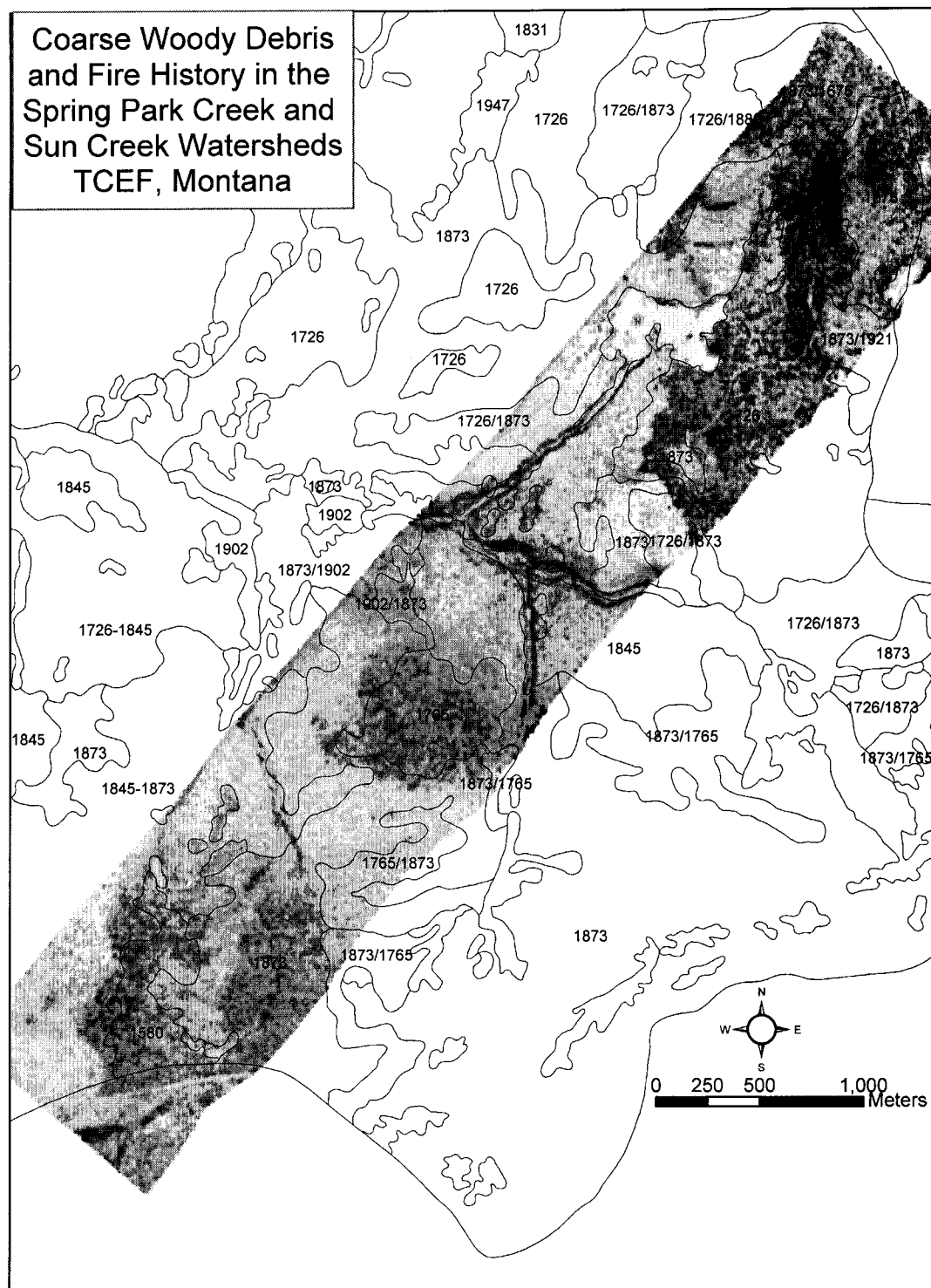


Fig. 6. Laser altimetry derived coarse woody debris loads overlain with Barrett's (1993) fire history. Darker shades represent heavy fuel accumulations. The geometric fidelity of the fuel map is high ($\pm 180\text{cm}$), but the fidelity of the photo interpretation-based fire history map is unknown.

units also show a high degree of correspondence with patterns in 1000-hr fuel load distribution. However, a number of units, particularly those associated with the 1873 fire do not appear to match the findings of Barrett (1993).

Figure 7 depicts the fuel polygons derived by the previously-described classification and filtering of the fuels data. These polygons provide the basis for a reasonably objective measure of correspondence between the fuels and fire history maps. The coefficient of areal correspondence (C_i) (Muehrcke and Muehrcke, 1992) allows the degree of association between fuel load and fire history to be assessed based on the proportion of overlap between the two. The coefficient is simply a ratio of the area where fuel load polygons overlap with fire history polygons to the area covered by either region. It ranges in value from 0 to 1, where 0 = no correspondence and 1 = perfect correspondence. Table 1 depicts these coefficients for the Spring Park and Sun Creek sub-watersheds.

Table 1. Coefficients of areal correspondence (C_i) between fire history regions and associated 1000-hr fuel load polygons for Spring Park and Sun Creek sub-watersheds within Tenderfoot Creek Experimental Forest

| Fire Year | C_i | Fire Year | C_i |
|-----------|-------|-----------|-------|
| 1580 | 0.586 | 1726/1873 | 0.588 |
| 1726 | 0.610 | 1726/1889 | 0.460 |
| 1765 | 0.666 | 1845-1873 | 0.435 |
| 1845 | 0.946 | 1873/1676 | 0.612 |
| 1873 | 0.439 | 1873/1765 | 0.428 |
| | | 1873/1902 | 0.277 |
| | | 1873/1921 | 0.746 |
| | | 1902/1873 | 0.423 |

***Regions with single fire history on left and regions with multiple fire history on right. The dominant age-class listed first for multiple fire regions.**

The coefficients of areal correspondence confirm what we can see by way of visual comparison (ie., there is general correspondence between fuels distributions and fire history). This correspondence is not surprising in the lodgepole-type forests at Tenderfoot, given that fire is the only significant disturbance mechanism documented in the region (Barrett, 1993), and it indicates that many of the landscape fuel patterns observed at Tenderfoot reflect fire history.

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The best correspondence generally occurs in isolated blocks with documented histories of single fires that occurred at least 250 years ago. An exception is the 1845 polygon (east-center), which burned more recently and is bounded by drainages that falsely appear to contain heavy fuels. In a sense, the bounding effect of these streams (which influences laser and fire history polygon delineation) results in an artificially high C_i value for the 1845 stand. Small, isolated regions characterized by multiple fires also correspond well with fire history. Agreements between fuel polygons and fire history polygons are less clear in larger regions associated with the 1873 fire. Here, a number of fuel polygons exist with distinct characteristics that may reflect a fire history different from the one proposed by Barrett (1993).

One of these polygons is the area of heavy fuel accumulation in what Barrett mapped as the 1873 fire in the southeast corner of the study area. This polygon is characterized by a mean fuel load of $5.812 \pm 1.551 \text{ kg/m}^2$, numbers similar to those found in the adjacent 1580 stand, the 1765 stand, and the 1726 stand. Although classified by Barrett (1993) as part of the 1873 fire, the region is clearly inconsistent with any of the other areas associated with the 1873 fire in terms of fuel loads. These other remnants of the 1873 fire have predicted mean fuel loads ranging from -0.975 to 1.526 kg/m^2 with standard deviations of 0.674 to 1.141 kg/m^2 . It is my belief that this area of heavy fuel accumulation might be a remnant of the 1580 or the 1765 fire given its fuel characteristics and its proximity to stands mapped by Barrett with those ages. However, because the region is so obvious in the optical imagery, it is difficult to imagine that Barrett overlooked it. Further fieldwork should resolve this issue, which highlights the utility of laser altimetry for aiding fire history studies.

There are a number of other incongruities between documented fire history and surface fuel distributions; notably, the 1726/1873 stand to the north and all combinations of 1873/1765 and 1873/1726. At this point, it would be unproductive to try to adjust Barrett's fire history based on fuel accumulations given the lack of knowledge about the relationships between coarse woody

debris distributions and fire activity, and in the absence of precise locations of Barrett's fire scar and tree core data. Further, it would be wise to accept some degree of cartographic error in stand boundary delineations on the fire history map. However, for those regions with obvious correspondence between fuels and fire history (i.e., 1580 and 1765 stands with C_i scores of 0.58 and 0.66, respectively), one could probably safely adjust the fire history boundaries to match those provided by the fuels map because the geometric fidelity of the laser altimetry data is high.

Although in the absence of alternative data, Barrett's (1993) interpretation of fire history is accepted as truth, it is worth noting that there is a considerable margin for alternative perspectives on fire history at Tenderfoot. Barrett utilized U.S.F.S. aerial photographs (scale and emulsion unknown) and a timber type map to draw stand age-class polygons, and used the resulting age-class mosaic to select sampling sites. Fire scars and stand initiation years were sampled at fifty sites in the Tenderfoot following Arno and Sneek (1977) and Barrett and Arno (1988) and were used to populate the age class mosaic map and to adjust preliminary stand boundaries. Unsampled stands, of which there were a considerable number, were labeled by extrapolating from nearby stands with similar crown appearance in aerial photographs.

Barrett's approach pre-supposes a link between canopy-based photomorphic units and fire history. This assumption is valid at the Tenderfoot, particularly when the last fire on a site was stand replacing, thus contradicting the widely held view that stands are not diagnostic of surface fuels. It is unknown whether Tenderfoot is unique in this regard. However, in many stands the most recent fire was not stand-replacing and there is clear evidence of two age classes within them. Further, because Tenderfoot's fire history is characterized by just a few large, spatially-juxtaposed fires (1726, 1765, 1845, 1873) that occurred relatively close in time to one another, the margins between them are often indistinct (Barrett, 1993). It is in these latter areas that there is substantial disagreement between fuel loads and Barrett's fire history. Not

coincidentally, these are also the regions in which photomorphic texture/tone patterns are indistinct in the optical imagery.

The potential utility of a fuel load map for refining fire history records in otherwise indistinct tracts of forest like those left behind by the 1873 fire is difficult to assess, but appears promising. In the simplest case whereby patches are characterized by single stand-replacing fire events, there may be a predictable relationship between coarse woody debris accumulations and time elapsed since last fire (Fig. 8). This graphic highlights at least two interesting fuel dynamics issues. First, landscapes that have not burned in the past 250+ years exhibit similar fuel characteristics, perhaps indicating that in the absence of other disturbance (insects, wind), coarse woody debris accumulation equilibrates with decomposition at ~250 years (~6 kg/m²). Second, younger stands with relatively little fuel accumulation (i.e. 1845, 1873), must be the result of at least two fires in reasonably close temporal proximity to one another, although there is no apparent evidence of the first fire/s. Otherwise, these stands should have relatively heavy fuel accumulations associated with standing debris from the most recent fire; debris that has subsequently fallen into the fuel bed.

In fact, several authors (Lieberg, 1904; Brown, 1975; Barrett, 1993) have noted the propensity for fire recurrence in post-fire fuels on landscapes like the one found at Tenderfoot. Barrett (1993) notes that most of the Tenderfoot's age-class mosaic is a function of just four fires occurring between 1726 and 1873. Casual observation of fire behavior by this author in lodgepole stands in Washington, Oregon, and Idaho suggest that these patterns exist elsewhere, and that fire activity in this forest type is as much a function of fuel dynamics related to recent fire activity as it is to more widely accepted causal factors like biophysical setting, average annual precipitation, and vegetation (Morgan et al., 2001). From a management perspective, these implications are significant because given the size and frequency of fires in the western United States since 1988, we might anticipate additional fire activity in the coming century where stand-

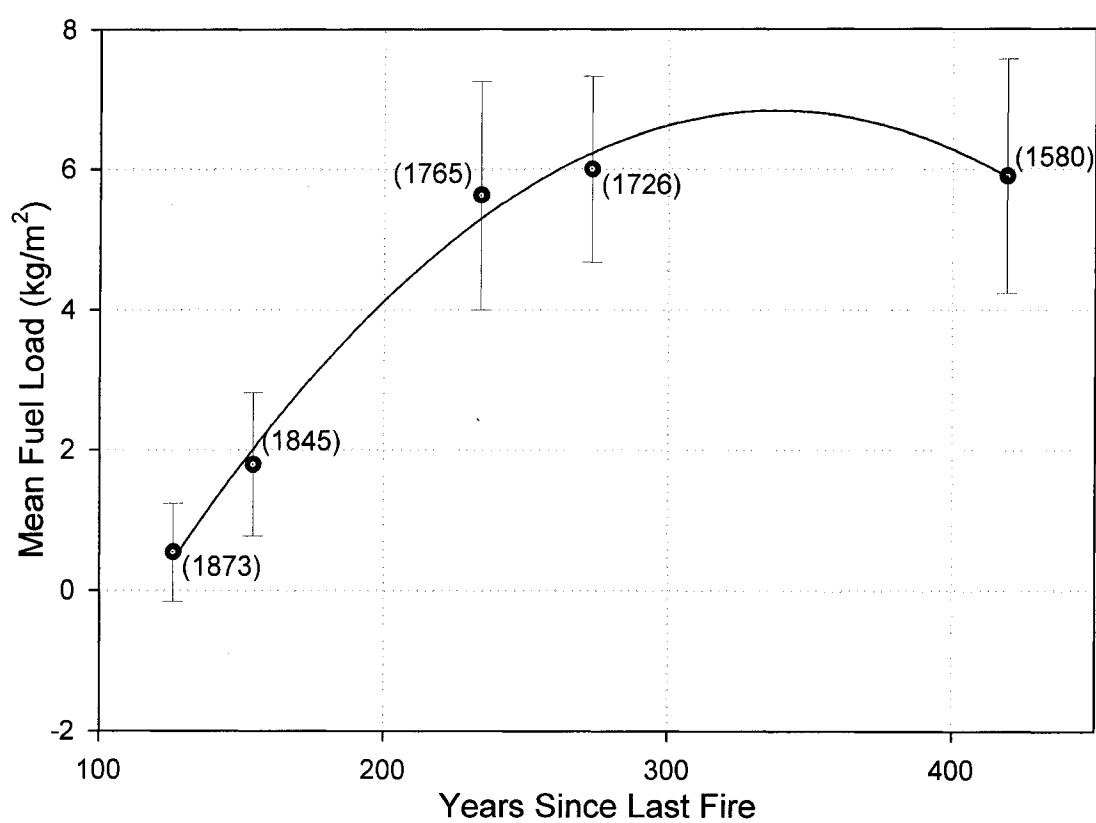


Fig. 8. In regions characterized by single fires, there is a roughly quadratic relationship between the timing of the fire and mean fuel load as estimated by laser altimetry. Numbers in paranthetics indicate year of fire.

replacing fire has already occurred. These areas should not be ignored when planning future suppression and treatment activities.

Conclusions

Plot-level relationships between airborne laser altimetry-derived surface roughness and field estimates of 1000-hr fuels allow coarse woody debris loads to be estimated effectively in lodgepole-type forests of west-central Montana. When applied to a landscape, these relationships continue to perform adequately, as indicated by comparisons with both plot-level and area-based field measurements. This form of remote sensing is clearly useful for consistent mapping of the spatial distribution of fuel accumulations and their within- and between-patch variability. However, laser altimetry appears unable to assist in discrimination of rough surfaces caused by the presence of coarse woody debris and those caused by geomorphic roughness. Further, the topographically diverse, narrow drainages that cross the study area appear to contain heavy fuel loads when in fact they probably contain very little.

Despite these issues, the ability of the technology to provide consistent, fine-grained fuels data across broad geographic areas is evident, and in the context of the cost, time, and energy associated with collecting such data, it reemphasizes the importance of clearly defining data requirements. In fuel types like those found at Tenderfoot, we finally have the means of collecting coarse woody debris data at a finer-grain than is probably necessary for most management applications. Future research, then, will attempt to identify optimal sampling rates for laser altimetry data that match the needs of the application at hand. One part of this work will include systematically *thinning* the Tenderfoot data to assess the quality of both fuel estimates and their spatial representation, as a function of sampling density (with the goal of minimizing cost and maximizing efficiency). A second part of this work will require that the fire managers and scientists who will use the fuels data clearly define their requirements for fuels information.

These requirements include but are not limited to boundaries on accuracy and precision, patch-size, and within- and between-patch variance. If all that is necessary are FBPS fuel models, laser altimetry is probably overkill, and Landsat-type spatial resolution optical imagery or aerial photographs would be sufficient. However, one potential advantage of using laser altimetry is that the data can be used for many things. They can be used to produce a precise digital elevation model with applications to geomorphology, soils, hydrology; to characterize canopy attributes with applications to silviculture, fire, wildlife; and to depict coarse woody debris with applications to fire, wildlife. It is this author's belief, then, that the most efficient future acquisitions of laser altimetry data will result from consultation with at least some of the diverse interests mentioned above.

At Tenderfoot, the 1000-hr fuels map is spatially consistent with independently-derived photomorphic units from high spatial resolution optical imagery and with fire history. Specifically, regions characterized by heavy fuel accumulations correspond with texturally rough canopies and the occurrence of single fires that burned at least 250 years ago. In regions with lighter fuel loads and more complex fire histories, these relationships break down, lending credibility to the notion that laser altimetry-derived fuel maps might be useful aids for documenting fire history in mixed-severity fire regimes characterized by episodes of frequent fire activity.

Certainly, appearance of the canopy as texturally distinct photomorphic units provides one indicator of fire history via the age-class maps of Barrett (1993), and coarse woody debris distributions provide another proxy of fire history. Are they compatible? In some cases, yes. Generally, where fire has not occurred for at least 250 years, canopy tone/texture is diagnostic of fuel accumulation. Where fires have recurred in post-fire fuels, the relationships are less clear. One might conclude that exploration of fuel distribution-fire history linkages is a productive area of future research that will only be possible with laser altimetry data. This technology appears to

be the only one capable of providing consistent and continuous fine-grained fuel estimates across large landscapes. Without doubt, the fuel maps produced in this study would have been very useful to Barrett when he developed his fire history sampling schema, and maps like it will likely help future investigations.

Finally, fire dynamics in the lodgepole-type ecosystem at Tenderfoot are much more complex than was previously thought, and demand further attention. Although in part this is a personal revelation based on prior ignorance, one cannot help but reconsider his thinking on fire dynamics in forests characterized by 'stand-replacing' events given the context provided by this research. We are now left to speculate, for example, about the consequences of fire suppression in stands that have burned recently. Should we expect a series of intense surface fires in these areas in the near future? How soon might they occur? How quickly will standing fuel return to the fuel bed? Without additional fire, will we be left with the unusual condition of mature lodgepole underlain by heavy fuel loads? These are the scientifically interesting questions that might be answered in part with the help of laser altimetry, and this is where I plan to go next with the technology.

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Appendix A

DATA DOCUMENTATION FROM SPENCER GROSS, INC.

Processed LIDAR Data White Sulfur Springs, Montana

Enclosed is a CDROM containing the following:

1. **Reflective Surface DEM:** Is the original processed LIDAR DEM for the whole project by flight lines as illustrated in the flight line index. A binary file has been generated for each flight line with the extension *.utm. Included on the CD is the software program "LIDAREXTRACT." This software is used to extract the returns of interest to an ASCII file. The resultant files contain three fields for Easting, Northing, and Ellipsoid height.

File names:

| | |
|-------------------|-------------------|
| 162107.utm | 165810.utm |
| 162920.utm | 170435.utm |
| 163630.utm | 171207.utm |
| 164320.utm | 173750.utm |
| 165124.utm | 174505.utm |

2. **Datum and Projection:** All coordinates are in UTM zone 12 NAD 83 meters for horizontal and ellipsoid height meters for the vertical.
3. **WhiteSulfurLidar.doc:** Digital copy of final report in MSWord format
4. **Readme.doc:** Description of delivered data files.

Appendix B

ACQUISITION PARAMETER SELECTION FROM SPENCER GROSS, INC.

Spencer B. Gross, Inc. requested LIDAR mapping over a forested area in White Sulfur Springs Montana. The project area was flown using EarthData Aviation's Navajo Chieftain, tail number N62912. The aircraft was equipped with the AeroScan LIDAR system, including an inertial measuring unit (IMU), and a dual frequency GPS receiver and antenna. The project area was flown on October 10-13, 1999.

Position and Orientation Data Collection and Processing

During the airborne data collection an additional GPS receiver was in constant operation, located on a temporary point set at the Great Falls International Airport and designated "GTF". The horizontal and vertical position of "GTF" was determined by a vector adjustment to the National Geodetic Survey (NGS) B order station "Q430", also referred to as "PID SS1239" (see attached NGS record document).

| Sta. | NAD 83 (1991) / WGS84 | | Ellip. Hgt. |
|------|-----------------------|------------------|-------------|
| Q430 | 47 27 56.17991 | -111 22 27.85521 | 1112.89 |
| GTF | 47 29 04.16727 | -111 21 13.22249 | 1103.01 |

Coordinate position of the GPS base station at the EarthData Aviation.

Ground Truth Determination

The kinematic GPS survey was performed using a vehicle mounted GPS antenna and receiver, mounted approximately above the driver at a height of 1.650 m above the ground, to collect profile data of several roadways within the project area. Base station GTF was used for this survey. Attached is a chart showing the job area including the flight lines, locations of the base station and the kinematic survey. This survey was used for accuracy verification of the processed LIDAR data.

GPS Data Processing

All GPS phase data was post processed with continuous kinematic survey techniques using "On the Fly" (OTF) integer ambiguity resolution. The GPS data was processed with forward and reverse processing algorithms. The results from each process were combined to yield a single fixed integer phase differential solution of the aircraft trajectory. Plots of altitude and the forward and reverse GPS solution residuals are attached. The variance of the forward to reverse solution difference was less than ± 6 cm in both the horizontal and vertical components, indicating a valid and accurate solution.

The IMU was used to record precise changes in position and orientation of the LIDAR scanner at a rate of 50 Hz. All IMU data was processed post flight with a Kalman filter to integrate inertial

measurements and precise phase differential GPS positions. The resulting solution contains geodetic position, omega, phi, kappa, and time for subsequent merging with the laser ranging information.

LIDAR Data Collection and Processing

The client requested three different acquisition modes for this mission which will be referred to as Mode A, Mode B, and Mode C.

Acquisition Mode A:

The areas of interest were flown at an altitude of 2743 meters (9000feet) above mean terrain. The LIDAR specifications follow:

| | |
|----------------------------|---------------|
| Flying Height | 2743 m AMT |
| Airspeed | 110-130 knots |
| Laser Pulse Rate | 15 kHz |
| Field of View | 5° |
| Scan Rate | 25.0 Hz |
| Average Swath Width | 239.54 m |

Acquisition Mode B:

The areas of interest were flown at an altitude of 2743 meters (9000feet) above mean terrain. The LIDAR specifications follow:

| | |
|----------------------------|---------------|
| Flying Height | 2743 m AMT |
| Airspeed | 106-135 knots |
| Laser Pulse Rate | 15 kHz |
| Field of View | 40° |
| Scan Rate | 11.0 Hz |
| Average Swath Width | 1996.89 m |

Acquisition Mode C:

The areas of interest were flown at an altitude of 1829 meters (6000 feet) above mean terrain. The LIDAR specifications follow:

| | |
|----------------------------|--------------|
| Flying Height | 1829 m AMT |
| Airspeed | 96-137 knots |
| Laser Pulse Rate | 15 kHz |
| Field of View | 15° |
| Scan Rate | 22.0 Hz |
| Average Swath Width | 481.53 m |

LIDAR, IMU, and GPS data were correlated using GPS time and processed using LIDAR post-processing software to determine the coordinate of each point on the ground. The AeroScan LIDAR is able to receive up to five returns from each laser shot fired. This allows receipt of return data from multiple objects as the laser beam travels towards the ground. For example, in a vegetated area, the laser beam may first hit the leaves of a tree (generating Return 1), then a branch (generating Return 2), and finally the ground (generating Return 3). This sequence may continue for up to five returns. All ranges have been corrected for atmospheric refraction and transmission delays. The resulting three dimensional coordinates are compiled in an ASCII mass point file of x, y, z on the UTM projection.

Initial evaluation of the LIDAR data was accomplished including comparison of the data from flight line to flight line and against the kinematic survey. The comparison with the kinematic survey yielded the following results:

| | |
|-----------------------------------|--------------|
| Vertical Accuracy | 14.5 cm RMSE |
| Standard Deviation | 10.2 cm |
| Mean Difference | 10.4 cm |
| Number of Points in Sample | 178 |

Following the accuracy assessment of the LIDAR data, it was determined that only two of the three required flight lines were flown in acquisition Mode C (see exhibit #3). At this time, there is no LIDAR data over this region which meets the acquisition requirements.

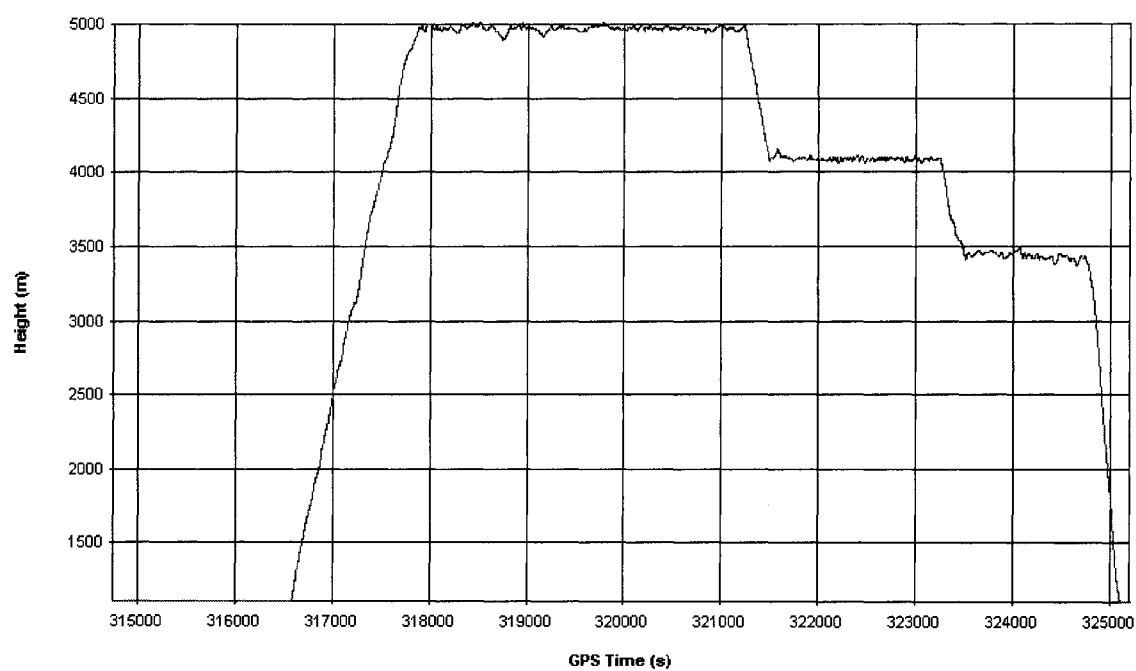
National Geodetic Survey record document:

1 National Geodetic Survey, Retrieval Date = FEBRUARY 18, 2000
 SS1239 *****
 SS1239 FBN - This is a Federal Base Network Control Station.
 SS1239 DESIGNATION - Q 430
 SS1239 PID - SS1239
 SS1239 STATE/COUNTY- MT/CASCADE
 SS1239 USGS QUAD - SOUTHWEST GREAT FALLS (1977)
 SS1239
 SS1239 *CURRENT SURVEY CONTROL
 SS1239
 SS1239* NAD 83(1992)- 47 27 56.17991(N) 111 22 27.85521(W) ADJUSTED
 SS1239* NAVD 88 - 1126.889 (meters) 3697.14 (feet) ADJUSTED
 SS1239
 SS1239 X - -1,574,630.848 (meters) COMP
 SS1239 Y - -4,023,274.005 (meters) COMP
 SS1239 Z - 4,677,733.509 (meters) COMP
 SS1239 LAPLACE CORR- 1.28 (seconds) DEFLEC99
 SS1239 ELLIP HEIGHT- 1112.89 (meters) GPS OBS
 SS1239 GEOID HEIGHT- -14.02 (meters) GEOID99
 SS1239 DYNAMIC HT - 1126.800 (meters) 3696.84 (feet) COMP
 SS1239 MODELED GRAV- 980,495.0 (mgal) NAVD 88
 SS1239
 SS1239 HORZ ORDER - B
 SS1239 VERT ORDER - FIRST CLASS II
 SS1239 ELLP ORDER - FOURTH CLASS II
 SS1239
 SS1239.The horizontal coordinates were established by GPS observations
 SS1239.and adjusted by the National Geodetic Survey in May 1992.
 SS1239
 SS1239.The orthometric height was determined by differential leveling
 SS1239.and adjusted by the National Geodetic Survey in June 1991.
 SS1239
 SS1239.The X, Y, and Z were computed from the position and the ellipsoidal ht.
 SS1239
 SS1239.The Laplace correction was computed from DEFLEC99 derived deflections.
 SS1239
 SS1239.The ellipsoidal height was determined by GPS observations
 SS1239.and is referenced to NAD 83.
 SS1239
 SS1239.The geoid height was determined by GEOID99.
 SS1239
 SS1239.The dynamic height is computed by dividing the NAVD 88
 SS1239.geopotential number by the normal gravity value computed on the
 SS1239.Geodetic Reference System of 1980 (GRS 80) ellipsoid at 45
 SS1239.degrees latitude (G = 980.6199 gals.).
 SS1239
 SS1239.The modeled gravity was interpolated from observed gravity values.
 SS1239
 SS1239; North East Units Scale Converg.
 SS1239;SPC MT - 359,000.222 458,778.389 MT 0.99942386 -1 22 16.1
 SS1239;UTM 12 - 5,256,975.209 471,783.940 MT 0.99960978 -0 16 33.2
 SS1239
 SS1239 SUPERSEDED SURVEY CONTROL
 SS1239
 SS1239 NAD 83(1986)- 47 27 56.18142(N) 111 22 27.83778(W) AD() 1
 SS1239 NAD 27 - 47 27 56.33593(N) 111 22 24.93767(W) AD() 1
 SS1239 NGVD 29 - 1125.95 (m) 3694.1 (f) LEVELING 3
 SS1239
 SS1239.Superseded values are not recommended for survey control.
 SS1239.NGS no longer adjusts projects to the NAD 27 or NGVD 29 datums.
 SS1239.See file dsdata.txt to determine how the superseded data were derived.
 SS1239
 SS1239_MARKER: I = METAL ROD
 SS1239_SETTING: 49 = STAINLESS STEEL ROD W/O SLEEVE (10 FT.+)

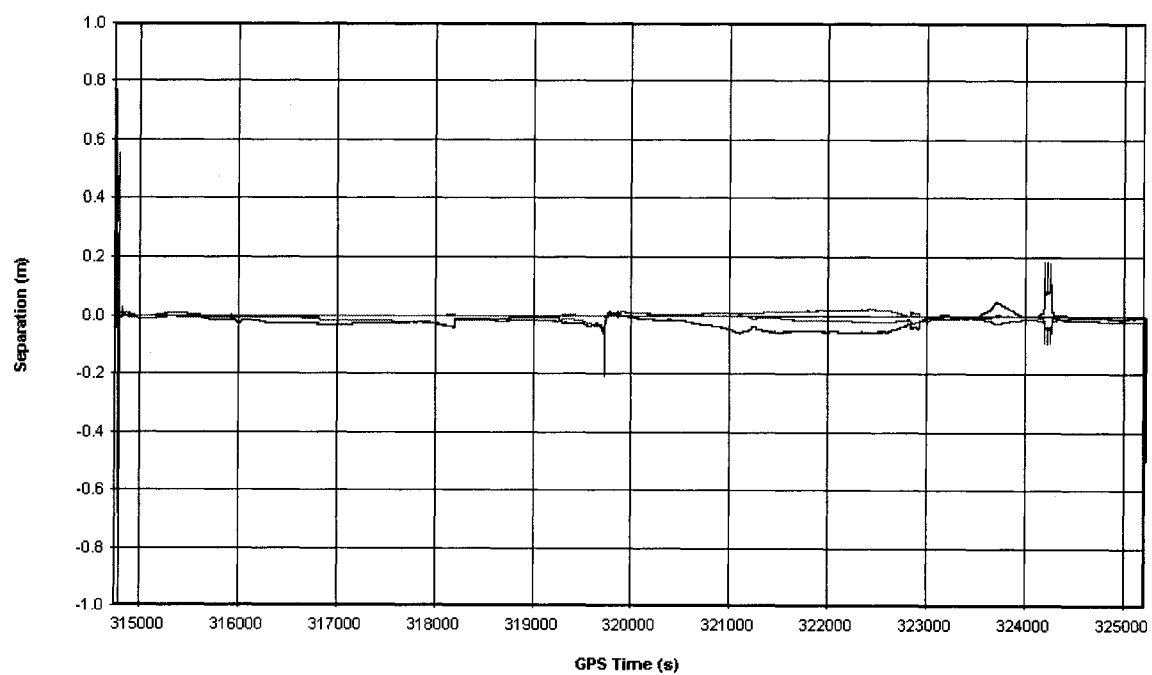
SS1239_STAMPING: Q 430 1979
 SS1239_PROJECTION: FLUSH
 SS1239_MAGNETIC: I = MARKER IS A STEEL ROD
 SS1239_STABILITY: B = PROBABLY HOLD POSITION/ELEVATION WELL
 SS1239_SATELLITE: THE SITE LOCATION WAS REPORTED AS SUITABLE FOR
 SS1239+SATELLITE: SATELLITE OBSERVATIONS - January 03, 1996
 SS1239_ROD/PIPE-DEPTH: 3.05 meters
 SS1239

| SS1239 HISTORY | - Date | Condition | Recov. By |
|----------------|------------|------------|-----------|
| SS1239 HISTORY | - 1979 | MONUMENTED | NGS |
| SS1239 HISTORY | - 19910826 | GOOD | NGS |
| SS1239 HISTORY | - 19941207 | GOOD | MTDOT |
| SS1239 HISTORY | - 19951216 | GOOD | MTDOT |
| SS1239 HISTORY | - 19960103 | GOOD | MTDOT |

 SS1239
 SS1239 STATION DESCRIPTION
 SS1239
 SS1239'DESCRIBED BY NATIONAL GEODETIC SURVEY 1979
 SS1239'2.0 MI SW FROM GREAT FALLS.
 SS1239'THE MARK IS ABOVE LEVEL WITH THE HIGHWAY.
 SS1239'2.0 MILES SOUTHWEST ALONG INTERSTATE HIGHWAY 15 FROM THE TENTH AVENUE
 SS1239'SOUTH OVERPASS IN GREAT FALLS, AT HIGHWAY MILE MARKER 277, 98.7
 SS1239'FEET NORTHWEST OF THE CENTERLINE OF THE SOUTHBOUND LANES OF THE
 SS1239'INTERSTATE HIGHWAY, 71.1 FEET NORTHWEST OF THE MILE MARKER, AND 1.6
 SS1239'FEET SOUTHEAST OF A BARBED WIRE FENCE. NOTE=DISK IS 4 INCHES BELOW
 SS1239'THE GROUND, ACCESS IS THROUGH A 4 INCH PLASTIC SCREW PLUG.
 SS1239'THE MARK IS 1.9 FT NE FROM A WITNESS POST.
 SS1239
 SS1239 STATION RECOVERY (1991)
 SS1239
 SS1239'RECOVERY NOTE BY NATIONAL GEODETIC SURVEY 1991
 SS1239'THE STATION IS LOCATED ON THE SOUTHWEST EDGE OF GREAT FALLS, ALONG THE
 SS1239'NORTHWEST RIGHT-OF-WAY OF INTERSTATE HIGHWAY 15, ABOUT 1.6 KM
 SS1239'(1.0 MI) SOUTH OF THE INTERNATIONAL AIRPORT AND AT MILE MARKER 277.
 SS1239'TO REACH THE STATION FROM THE JUNCTION OF INTERSTATE HIGHWAY 15 AND
 SS1239'10TH AVENUE SOUTH, IN SOUTHWEST GREAT FALLS, GO SOUTHERLY ON
 SS1239'INTERSTATE HIGHWAY 15 FOR 3.2 KM (2.0 MI) TO THE STATION ON THE RIGHT
 SS1239'IN A FENCE ROW.
 SS1239'THE STATION IS A BENCH MARK DISK SCREWED TO THE TOP OF A STAINLESS
 SS1239'STEEL ROD AND ENCASED IN A 3.5 INCH PVC PIPE. LOCATED 30.08 M
 SS1239'(98.69 FT) NORTHWEST OF THE CENTER OF THE SOUTHBOUND LANE OF
 SS1239'INTERSTATE HIGHWAY 15, 21.64 M (71.00 FT) NORTHWEST OF MILE MARKER
 SS1239'277, 0.58 M (1.90 FT) NORTHEAST OF AND NEXT TO A METAL WITNESS POST
 SS1239'AND 0.48 M (1.57 FT) SOUTHEAST OF THE HIGHWAY FENCE.
 SS1239
 SS1239 STATION RECOVERY (1994)
 SS1239
 SS1239'RECOVERY NOTE BY MONTANA DEPARTMENT OF TRANSPORTATION 1994 (DRD)
 SS1239'RECOVERED AS DESCRIBED.
 SS1239
 SS1239 STATION RECOVERY (1995)
 SS1239
 SS1239'RECOVERY NOTE BY MONTANA DEPARTMENT OF TRANSPORTATION 1995 (DRD)
 SS1239'RECOVERED AS DESCRIBED.
 SS1239
 SS1239 STATION RECOVERY (1996)
 SS1239
 SS1239'RECOVERY NOTE BY MONTANA DEPARTMENT OF TRANSPORTATION 1996 (DRD)
 SS1239'RECOVERED AS DESCRIBED.



Altitude Plot



Forward-Reverse Solution Residuals

Appendix C

LIDAR DATA EXPLORATION NOTES

Spencer Gross provided three CD's with data. The first contains raw returns arranged in flightlines for each acquisition mode. A DOS extraction utility (LidarExtract.exe) generates ASCII text files for each flightline. Each record (a single shot) contains space delimited easting, northing, and height (meters) above ellipsoid. The utility requires file name, return number (1-5, L, A, O, N), Elevation Min., Elevation Max., and Decimate. The Decimate feature does not appear to affect number of records extracted when A (All) or L (Last) returns are selected. In reality, decimate should remove every nth record.

The second CD contains noise-filtered (corrected) returns arranged in the same flightlines as the first CD. A DOS extraction utility (LidarExtractSA.exe) is provided- identical to LidarExtract.exe except that it appends scan angle to each record extracted.

The third CD contains canopy and ground returns for each flightline as separate files.

Initial exploration of flightline 164320 indicates that 8.7 percent of records are removed when the raw data are converted to reflected surfaces (presumably due the negative noise pitting problem described in processing notes). Also, as much as 24 percent of the corrected dataset is multiple return. Specifically:

0 records at 5th return
 31 records at 4th return
 20,357 records at 3rd return
 489,905 records at 2nd return
 1,611,649 records at 1st return
 FOR A TOTAL OF 2,121,942 total records.

The above is actually not true. The reflected surface files contain 8-10 percent fewer records than the raw files (all missing records are second returns). However, the negative noise is not removed from the reflected surface file, so it is not clear why these points are in one file but not in the other.

For this reason, I have chosen to use the raw data (without scan angle) for the original data exploration. I extracted the seven flightlines of acquisition mode A using the lidarextract.exe utility (N). The number of records posted by the utility do not match the actual number of records. Actual record numbers are outlined below:

| | |
|-----------|---------|
| a1_rn.txt | 2790112 |
| a2_rn.txt | 2409472 |
| a3_rn.txt | 2333203 |
| a4_rn.txt | 2322914 |
| a5_rn.txt | 2355520 |
| a6_rn.txt | 2295264 |
| a7_rn.txt | 2648362 |

Appendix D

EXTRACTION UTILITY NOTES

The extraction utility allows the user to extract data from a flightline in various ways.

The N extraction returns a file (.rn) with shot number, return number (per pulse), easting, northing, and height above datum for all returns in the flightline.

The A extraction returns a file (.all) with easting, northing, and height above datum. It is the same file as obtained with the N extraction, but does not contain shot number or return number.

The O extraction returns two files (.sin and .fin). The .sin file contains all single returns in the flightline and the .fin file returns only the last returns of multi-return datasets (easting, northing, height above datum for both files).

The L extraction returns a file (.rl) that contains the last returns for the flightline. This file is equivalent to .sin+.fin.

The 1 extraction returns a file (.r1) that contains all first returns (including single returns). For first returns of multi-return points, the first return is highest in the canopy.

The 2,3,4,5 extractions return files (.r2, .r3 ...) containing 2nd, 3rd, 4th, and 5th returns, respectively. Each successive return is lower in the canopy than the previous return. Further, the eastings and northings for each return in a multi-return shot are different, suggesting that the x,y,z location is calculated independently for each return (In fact, this last point is true).

With regard to this last point: The data were collected in three acquisition modes. The FOV for mode 1 is 5 degrees, mode 2 is 40 degrees and mode three is 15 degrees.

For a 30 meter tall canopy with a return from canopy top:

The ground return will be, at most, 1.31 meters offset horizontally in Mode 1 (farthest off-nadir).

The ground return will be 10.91 meters offset in Mode 2.

The ground return will be 3.95 meters offset in Mode 3.

Further, the path from canopy top to ground at extreme off nadir (with a 30 meter canopy) will be:

30.03 meters in Mode 1.

31.9 meters in Mode 2.

30.26 meters in Mode 3.

Appendix D

RAW DATA RECORD INFORMATION

| Flightline | Number of Returns | | | | |
|-------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|
| | 1st returns | 2nd returns | 3rd returns | 4th returns | 5th returns |
| 162107.all | 1967492 | 629109 | 23178 | 17 | 0 |
| 162920.all | 1666735 | 552125 | 18333 | 6 | 0 |
| 163630.all | 1624392 | 496141 | 19214 | 23 | 0 |
| 164320.all | 1611649 | 489905 | 20357 | 31 | 0 |
| 165124.all | 1648117 | 496247 | 21335 | 33 | 0 |
| 165810.all | 1638561 | 450059 | 19505 | 21 | 0 |
| 170435.all | 1926303 | 498803 | 22051 | 26 | 0 |

Total # returns

| | |
|------------|---------|
| 162107.all | 2619796 |
| 162920.all | 1666735 |
| 163630.all | 1624392 |
| 164320.all | 1611649 |
| 165124.all | 1648117 |
| 165810.all | 1638561 |
| 170435.all | 1926303 |

* .all files contain easting, northing, height above datum.

Appendix E

EQUATIONS RELATING PLOT-LEVEL FIELD AND LASER FUEL METRICS (CHAPTER 3)

| | TOTVOL | r2 | 1KVOL | r2 | LT1KVOL | r2 |
|------|-----------------------|------|---------------------|------|----------------------|------|
| OD | $y=47.091x+.0168$ | 0.78 | $y=4.533x-.1757$ | 0.78 | $y=1.758x+.1924$ | 0.3 |
| SD | $y=17.134x-3.324$ | 0.7 | $y=16.500x-3.394$ | 0.71 | $y=.6340x+.0701$ | 0.26 |
| KURT | $y=49.286/x+.0331$ | 0.75 | $y=47.466/x-.1540$ | 0.76 | $y=1.921/x+.1871$ | 0.28 |
| | TOTLOAD | | 1KLOAD | | LT1KLOAD | |
| OD | $y=40.905x+.1259$ | 0.78 | $y=38.336x-.1564$ | 0.79 | $y=2.569x+.2823$ | 0.3 |
| SD | $y=14.903x-2.784$ | 0.71 | $y=13.954x-2.878$ | 0.71 | $y=.9494x+.0939$ | 0.27 |
| KURT | $y=43.146/x+.1211$ | 0.77 | $y=40.296/x-.1501$ | 0.77 | $y=2.850/x+.2712$ | 0.29 |
| | TOTSUR | | 1KSUR | | LT1KSUR | |
| OD | $y=1283.702x+77.837$ | 0.67 | $y=844.787x+7.258$ | 0.76 | $y=438.915x+70.579$ | 0.37 |
| SD | $y=475.853x-16.894$ | 0.63 | $y=308.799x-53.260$ | 0.69 | $y=167.054x+36.367$ | 0.37 |
| KURT | $y=1389.470/x+74.944$ | 0.69 | $y=885.389/x+7.596$ | 0.74 | $y=504.077/x+67.349$ | 0.41 |

OD- Obstacle density

SD- Standard deviation of ground height distribution (GHD)

KURT- Kurtosis of GHD

TOTVOL- Total volume

1KVOL- 1000-hr fuel volume

LT1KVOL- 1+10+100hr fuel volume

TOTLOAD- Total load

1KLOAD- 1000-hr fuel load

LT1KLOAD- 1+10+100hr fuel load

TOTSUR- Total surface area

1KSUR- 1000-hr fuel surface area

LT1KSUR- 1+10+100hr surface area

OBSERVED VERSUS PREDICTED r2

| | TOTVOL | 1KVOL | LT1KVOL |
|------|---------|--------|----------|
| OD | 0.82 | 0.80 | 0.32 |
| SD | 0.82 | 0.81 | 0.33 |
| KURT | 0.80 | 0.79 | 0.29 |
| | TOTLOAD | 1KLOAD | LT1KLOAD |
| OD | 0.82 | 0.80 | 0.31 |
| SD | 0.81 | 0.80 | 0.33 |
| KURT | 0.79 | 0.78 | 0.29 |
| | TOTSUR | 1KSUR | LT1KSUR |
| OD | 0.77 | 0.87 | 0.47 |
| SD | 0.73 | 0.88 | 0.47 |
| KURT | 0.66 | 0.84 | 0.44 |