APPLICATIONS OF LIDAR IN WILDFIRE MANAGEMENT

AN OPPORTUNITY IN BRITISH COLUMBIA

Janice Burns
FRST 497

4/1/2012

ABSTRACT

British Columbia’s Wildfire Management Branch is undergoing a transformation from reactive to proactive fire management. They are seeking to prioritize fuel management treatments in the wildland-urban interface, and identify areas where it would be beneficial to monitor rather than suppress fire. This paper examines the uses of Lidar in fire science and investigates ways that Lidar could be used to improve fire management in British Columbia. Discrete return, ‘small footprint’ Lidar is a commonly used active remote sensing system in the natural resources field. It produces highly accurate measurements of forest structure in three-dimensions and fire management plans could benefit from using Lidar to locate and prioritize areas for fuel management treatments and prescribed burning. Fire analyses and suppression could benefit from improved fire growth information based on detailed measurements of canopy base height, crown bulk density, canopy height, ladder fuels, fuel size, vertical fuel continuity, and horizontal arrangement of fuels. These measurements can be used to create fuel maps which are suitable inputs for decision support systems that model fire behaviour and spread. Lidar data seems expensive, but it is worthwhile when it leads to reduced costs through improved decision making in wildfire management.

KEYWORDS

digital elevation model, digital terrain model, fuel type, fuel map, proactive management, remote sensing, Wildfire Management Branch, wildland-urban interface

TABLE OF CONTENTS

Abstract i

Keywords i

List of Tables iii

List of Figures iii

Introduction 1

Background 1

What is Lidar? 2

How is Lidar being used in fire science globally? 5

- Digital Terrain Models (DTMs) 5
- Fuel Maps 7

How could Lidar be used in British Columbia? 11

- Fire Management Planning 11
- Fire Analysis 11

Implementation 12

Conclusion 13

References 14

LIST OF TABLES

Table 1: Wildfire management terminology (Forest Practices Board 2012, Forest Practice Board 2010, Province of British Columbia 2010). 2

Table 2: Glossary of Lidar terminology. "Definitions are based largely on information found in Baltsavias (1999), Maune (2001), Lefsky et al. (2002) and Lim et al. (2003)," (adapted from Wulder et al. 2008)...... 3

Table 3: Glossary of fire science terminology. Definitions are based largely on information found in Erdody and Moskal (2010), Arroyo et al. (2008), Scott and Reinhardt (2007), and Riaño et al. (2003). 8

LIST OF FIGURES

Figure 1: Airborne Lidar data acquisition (Kao et al. 2005)........ 4

Figure 2: Discrete-return Lidar systems differ from waveform Lidar systems because they record up to five discrete-returns along the path of laser illumination whereas waveform Lidar records a continuous return signal (Lefsky et al. 2002). 4

Figure 3: Multiple Lidar returns from the canopy (A), the understory (B), and ground (C) displayed above a digital terrain model (D) interpolated from ground data (Shuckman and Renslow 2012). 5

Figure 4: TRIM 20m digital terrain model (left) compared to Lidar 1.5m digital terrain model (right) (Bater and Coops 2009)........ 6

Figure 5: Canopy fuel metrics (Erdody and Moskal 2010). 8

Figure 6: The digital surface model (A) shows the true elevation of the top of the canopy, the digital terrain model (B) shows the underlying surface elevation, and the digital canopy model (C) shows vegetation and tree heights. The digital canopy model (C) is created when the DTM (B) is subtracted from the DSM (A) (Clark et al. 2004). 9

INTRODUCTION

As remote sensing technologies become more widely available and affordable, many researchers are investigating the use of Light Detection and Ranging (Lidar) in fire science. Lidar has proven to be very well suited to producing high-quality digital terrain models and fuel maps by measuring the three-dimensional structure of the forest and surface topography (Andersen et al. 2005). The ability to measure vertical forest structure distinguishes Lidar from other remote sensing technologies and brings it to the attention of progressive wildfire management agencies. Lidar has yet to be integrated in fire science in British Columbia on a large scale, but increasing implementation in the United States, and the progressive nature of the Wildfire Management Branch suggest that it could be possible in the near future. The objective of this paper is to investigate the applications of Lidar in fire science and explore how Lidar might be able to help the Wildfire Management Branch reach their goals of proactive management and global excellence.

BACKGROUND

British Columbia aspires to have one of the best wildland fire management agencies in the world—the Wildfire Management Branch. This agency, formerly the known as the Protection Branch, has been very successful in suppressing fires in the province, annually controlling 92% of all wildfires before they reach four hectares in size (Wildfire Management Branch 2011). However, they have recently identified that the traditional emphasis on 'fire control', through fire suppression, may not be suitable for long-term forest management that aims to sustain timber extraction, biodiversity, and forest resilience to environmental change. As a result, they are now focusing on 'wildfire management', which is meant to incorporate fire as a natural disturbance agent in forest ecosystems, while using fire suppression to protect people, property, and resources as necessary (Forest Practices Board 2012). The Wildfire Management Branch aspires to be a world leader in sustainable environmental management and they claim that their new commitment to wildfire management will help realize this vision of global excellence (Province of British Columbia 2010).

A changing fire environment presents a number of challenges for the Wildfire Management Branch. In recent years, the cost and severity of fires has increased dramatically (Province of British Columbia 2010). Several factors are to blame for the increased severity including years of dry weather, insect infestations, and successful fire suppression (Province of British Columbia 2010). In addition, provincial population growth has led to an increase in the number of permanent residences, recreational homes, and facilities located in the wildland-urban interface (Province of British Columbia 2010). The expansion of this zone has increased the probability of fires threatening human life and safety, or property, which demands that more fires must be controlled aggressively thus increasing the cost of suppression (Forest Practices Board 2012). As the fire environment evolves in British Columbia, so must the Wildfire Management Branch.

A change from reactive to proactive management is expected to reduce the burden of wildfire management on public finances. A recent report released by the Forest Practices Board emphasizes the need for British Columbia to focus on proactive measures of fire management to reduce the financial burden of management activities (Forest Practices Board 2012). The report notes that increased fire suppression resources alone will not be able to solve the problems facing the province because it is not possible, efficient, or necessarily desirable to suppress every fire (Forest Practices Board 2012). However, it recommends that extra effort, funding, and innovation be directed towards improving provincial fire management plans and fire analyses so that the Wildfire Management Branch will be prepared to allocate resources efficiently when unwanted fires occur and identify beneficial fires and allow them to burn (Forest Practices Board 2012). It also encourages the province to comply with the recommendations of the British Columbia Wildland Fire Management Strategy. The Wildland Fire Management Strategy emphasizes the importance of proactive management stating, "A strategic shift is needed to proactively manage the benefits and risks of wildland fire to meet the immediate and longer-term needs of society,"(Province of British Columbia 2010). Investment in Lidar technology may help the Wildfire Management Branch to improve their fire management plans, fire analyses, and fully implement the Wildland Fire Management strategy. Fire management terminology is described in Table 1.

Table 1: Wildfire management terminology (Forest Practices Board 2012, Forest Practice Board 2010, Province of British Columbia 2010).

Term	Definition
Fire Analysis (FA)	A document prepared after a wildfire starts that identifies the values at risk if a fire grows, including public safety, private land, parks, timber and environmental values. The FA sets out the general fire control objectives, strategies and tactics, and alternatives. It estimates the cost of suppression and sets out trigger points where the FA must be reconsidered. An FA is developed in consultation with the land manager. An FA must be completed when initial attack fails, and for all fires where modified response is contemplated.
Fire Management Plan (FMP)	A document prepared by the land manager (district manager or parks manager) before a fire starts that identifies values, priorities, and restrictions on practice to assist wildfire managers during wildfire management and wildfire control activities. In future, FMPs will be expanded to include guidance on fuels management and prescribed fire.
Wildland Fire Management Strategy (WFMS)	A guidance document that encourages the reduction of fire hazard around communities, the careful use of controlled burning, the tactic of monitoring and managing rather than suppressing low-risk fires, the implementation of fire management planning, and the development of public awareness about wildfire management.
Wildland-urban Interface (WUI)	An area where human development meets or is intermingled with forest and grassland fuel types.

WHAT IS LIDAR?

Lidar is a high-resolution, active, airborne, remote sensing system that can provide accurate, three-dimensional models of forest structure and surface topography (Lefsky et al. 2002). Active sensors differ from passive sensors (such as Landsat Thematic Mapper and aerial photography) because they use their own energy rather than relying on radiation from the sun (Wulder et al. 2008). Lidar sensors are typically airborne—mounted on helicopters or fixed wing aircraft. Unlike conventional remote sensing systems, which only produce two-dimensional images, Lidar is able to measure forest canopies, understory vegetation, and topography below the main canopy in three dimensions (Lefsky et al. 2002). This can be achieved through Lidar's unique method of collecting data.

Some terminology pertaining to the use, acquisition, and processing of Lidar is described in Table 2.

Table 2: Glossary of Lidar terminology. "Definitions are based largely on information found in Baltsavias (1999), Maune (2001), Lefsky et al. (2002) and Lim et al. (2003)," (adapted from Wulder et al. 2008).

Term	Definition
canopy height model (CHM)	A continuous digital dataset representing vegetation heights. Also referred to as a digital canopy model (DCM).
digital elevation model (DEM)	A continuous digital dataset representing terrain heights. Created by applying an interpolation routine to ground returns. Also commonly referred to as a digital terrain model (DTM).
discrete return	A Lidar system that records reflected pulses as discrete points in three-dimensional space. State-of-the-art sensors may record multiple returns for each emitted pulse.
filtering	Classification of LiDAR returns with reference to the surfaces from which they were reflected, such as ground, non-ground, vegetation, building, and so on. Though automated to some degree, a significant amount of operator intervention is often required.
footprint	The diameter of a laser pulse's circle of illumination on the ground. LiDAR sensors may be small footprint (typically 0.1-2 m) or large footprint (typically 10-100 m).
ground returns	Laser pulse returns that have been classified as having been reflected by the ground.
inertial navigation system	A component of a LiDAR system that records the pitch, roll and yaw of the aircraft to correct the orientation of the sensor at the time of pulse emission.
interpolation	The estimation of values at unsampled locations within the range of a set of measured points. Natural neighbour, splining, and kriging are commonly used algorithms employed to generate continuous digital elevation and canopy height models from LiDAR returns.
light detection and ranging (LiDAR)	An active remote sensing system employing a laser to measure distance to a target. Currently, the majority employed operationally are airborne, discrete return, small footprint systems. Also referred to as laser altimetry.
non-ground returns	Laser pulse returns that have been classified as having intercepted surfaces above the ground, such as vegetation or buildings.
pulse	A laser pulse generated and emitted from the LiDAR sensor.
return	A pulse that is reflected off a target and returned to a detector on the LiDAR sensor and recorded.
waveform recording	A LiDAR system with the capacity to continuously measure reflected radiation through a vertical profile. May be referred to as "full waveform data."
wavelength	The distance between successive peaks of an electromagnetic wave. Near-infrared lasers are typically employed for terrestrial mapping applications. Expressed in micrometres (μm) or nanometres (nm).

The basic principle of Lidar is that a sensor emits a high frequency laser pulse of near infrared (NIR) light and the return of that pulse is recorded along with the elapsed time. The time can be multiplied by the speed of light and divided by two (accounting for the return trip) to obtain the distance between the sensor and the reflecting surface (Lefsky et al. 2002). Wavelengths between 900 and 1064 nanometers are typically used in forest inventories because vegetation has high transmittance and reflectance values in this range (Lefsky et al. 2002). This allows for excellent measurements of forest canopy structure and understory structure. A downside of using NIR is that it is absorbed by water, so clouds and overcast conditions can prevent the sensor from making accurate measurements (Lefsky et al. 2002).

To determine the exact source location of a laser return, four precision instruments are required including: (1) a global positioning system (GPS), (2) an inertial navigation system (INS), (3) an angle encoder, and (4) a clock (Lefsky et al. 2002). The combination of these elements allows Lidar to record the absolute position of reflective surfaces such as tree canopies, understory vegetation, and the ground surface (Lefsky et al. 2002). Figure 1 illustrates an example of a fixed-wing aircraft with a basic airborne Lidar system. The GPS identifies the location of the platform, and the INS measures the attitude (roll, pitch, and yaw) of the sensor (Lefsky et al. 2002). The angle encoder measures the orientation of the scanning mirror, and the clock measures the time between when a pulse is emitted and received (Lefsky et al. 2002).

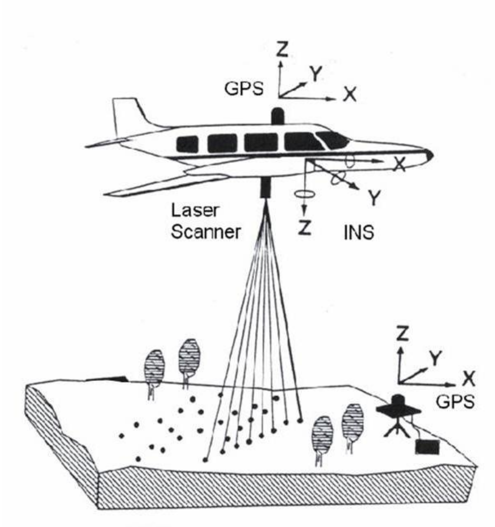

Figure 1: Airborne Lidar data acquisition (Kao et al. 2005).

The ability to pinpoint locations is also determined by the type of Lidar system that is used. Some systems are better for measuring the detail of individual tree crowns and small-scale spatial heterogeneity while others are more suited to the landscape scale (Morsdorf et al. 2004). Discrete-return and waveform are two Lidar systems for receiving laser pulse returns after they are emitted from the sensor and reflected back from a surface (Lefsky et al. 2002).

Discrete-return systems have a high spatial resolution and are used to detect fine-scale or 'small-footprint' variation. These systems can record single returns such as the first or last pulse associated with an object, or up to five discrete returns (Lefsky et al. 2002). The first pulse typically indicates a point near the top of a tree crown, while the final pulse often indicates the ground surface (Lefsky et al. 2002). Using two to five pulse returns provides more information on height and arrangement of branches and vegetation in the understory and suppressed layers than a single return (Lefsky et al. 2002).

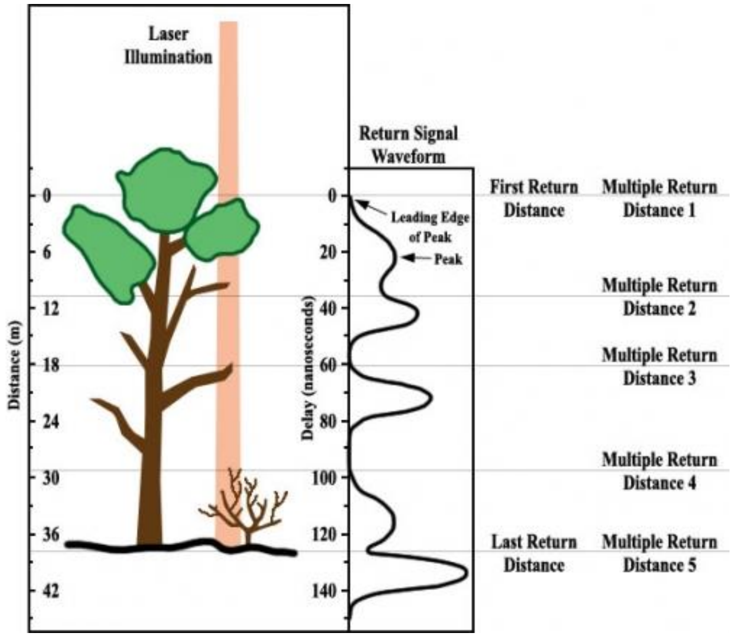

Figure 2: Discrete-return Lidar systems differ from waveform Lidar systems because they record up to five discrete-returns along the path of laser illumination whereas waveform Lidar records a continuous return signal (Lefsky et al. 2002).

Waveform systems record a continuous return from a pulse (which may include tens of thousands of responses) but they lack the spatial resolution of discrete-return Lidar, resulting in a 'large footprint' representation of the site (Lefsky et al. 2002). The distinction between discrete-return and waveform Lidar is illustrated in Figure 2. The most commonly used system in natural resources management is small-footprint Lidar because it produces the same parameters that are available from waveform Lidar, but on a scale of about 1m as opposed to 10-15m with waveform Lidar (Morsdorf et al. 2004).

HOW IS LIDAR BEING USED IN FIRE SCIENCE GLOBALLY?

DIGITAL TERRAIN MODELS (DTMS)

Airborne laser altimetry is an excellent tool for measuring surface topography and is commonly used to produce digital terrain models (DTMs) and digital elevation models (DEMs) because of its efficiency and ability to record elevation information below vegetation cover. Surveying and photogrammetry have traditionally been used to create DTMs but they are constrained because surveying is time consuming and labour intensive, and photogrammetry is only accurate in areas where the ground surface is not obscured by vegetation (Lefsky et al. 2002) or shadow (Erdody and Moskal 2010). Airborne Lidar is less sensitive to vegetation cover than photogrammetry (Lefsky et al. 2002). Additionally, elevation information can be collected quickly over large areas and relatively little labour is required because large volumes of data can be processed electronically (Morsdorf et al. 2004). Compared to old methods of determining elevation, Lidar is very cost effective (Lefsky et al. 2002)

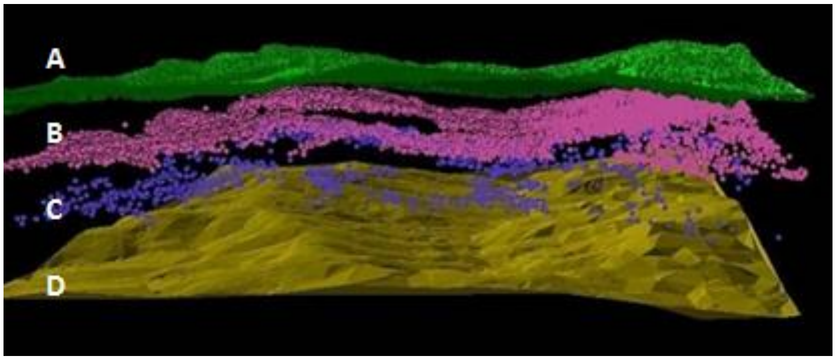

Figure 3: Multiple Lidar returns from the canopy (A), the understory (B), and ground (C) displayed above a digital terrain model (D) interpolated from ground data (Shuckman and Renslow 2012).

Lidar DTMs are created using the last response to return to the sensor from a laser pulse and they are refined using filtering algorithms to remove any non-ground responses created by trees or understory vegetation (Lefsky et al. 2002, Morsdorf et al. 2004). When a pulse of Lidar is sent out, the first returns to get back to the sensor usually come from the tallest trees and the top of the canopy, after that returns come from the midstory and understory vegetation (Lefsky et al. 2002). The final return usually represents the ground surface and is used to create DTMs and DEMs (Lefsky et al. 2002). An example of canopy, understory, ground responses, and the resulting DTM is shown in Figure 3.

In some circumstances, Lidar can be ineffective due to an obscuring layer of vegetation, but generally the Lidar illumination can penetrate all the way to the ground—passing through very small canopy gaps (Lefsky et al. 2002). If the ground is completely obscured by vegetation, the understory may be mistaken for the ground surface and therefore the ground surface elevation would be overestimated (Lefsky et al. 2002) but Lidar remains an effective tool for measuring elevation in most vegetated areas. A study in an extremely dense and structurally complex section of old-growth tropical rainforest in north-east Costa Rica found that Lidar could be used to create DTMs with accuracies better than that which is required for the highest quality publicly available DTMs in the United States (RMSE 7m)(Clark et al. 2004). The RMSE of 1.95m was the greatest error obtained in this complex old-growth forest, which was much less than the allowable RMSE of 7m (Clark et al. 2004). The level of accuracy in dense forest conditions is significantly lower than in areas of open canopy, but even in very dense vegetation Lidar can provide good results (Clark et al. 2004).

There are many current uses for high-resolution topographic Lidar information. Lidar-derived DTMs can be extremely detailed with absolute positional accuracies below 15cm in the vertical dimension and 50cm in the horizontal dimension (Morsdorf et al. 2004). The high spatial resolution of 1.5m Lidar is apparent when compared to 20m Terrain Resource Information Management (TRIM) data in Figure 4. Because Lidar is so accurate, it can be used by engineers and many others. Applications of Lidar derived DTMs include: engineering and flood plain analysis (Clark et al. 2004), road building and harvest block layout (Means et al. 2000), landslide analysis, and corridor mapping for pipelines and telecommunications (USDA Forest Service Remote Sensing Applications Center 2009), as well as mapping of dynamic features such as polar ice sheets and sand dunes (Krabill et al. 2000, Krabill et al. 1999). Several recent studies have investigated the use of Lidar DTMs in fire management and fire behaviour prediction.

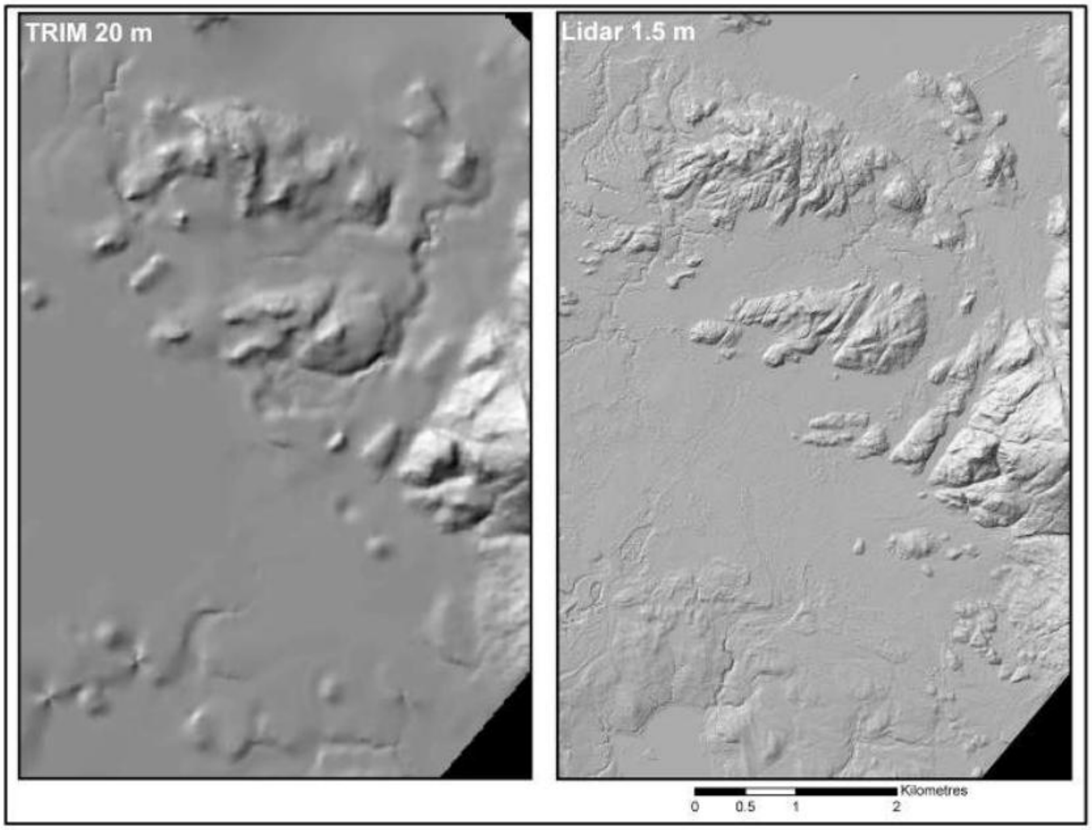

Figure 4: TRIM 20m digital terrain model (left) compared to Lidar 1.5m digital terrain model (right) (Bater and Coops 2009).

In fire management, DTMs can be used as topographic inputs or as base elevation maps, which can be subtracted from canopy and vegetation heights to assess fuels. Topographic information such as slope, elevation, and aspect can be used as direct inputs into decision support systems such as FARSITE (Fire Area Simulator) and BEHAVE (Fire behavior prediction and fuel modeling system) (Morsdorf et al. 2004). These inputs are essential to successful fire behaviour prediction modeling. Digital terrain models also provide the base elevation which is subtracted from digital surface models (DSMs) to estimate vegetation heights and fuel loading (Andersen et al. 2005, Lefsky et al. 2002, Morsdorf et al. 2004, Clark et al. 2004).

One potential problem with the use of Lidar for DTMs in British Columbia is that its accuracy is reduced on slopes (Clark et al. 2004). Many of the studies took place on flat ground or they stopped measuring at a maximum 70% slope. The reason for this is that there are fewer ground returns for a given elevation as the slope increases (Clark et al. 2004). Nonetheless, a study in structurally complex old growth, found that the increase in DTM RMSE from flat ground to a 44-degree slope was just 0.67m (Clark et al. 2004).

FUEL MAPS

Traditional qualitative fuel assessments have been criticized for their inability to capture the spatial heterogeneity of fuels at stand and landscape levels, leaving decision makers open to criticism or consequence when relying on these assessments. In contrast, Lidar offers an opportunity to apply quantitative measures of estimating fuel loads at a range of spatial scales that are important for fire management. Historically, fuel maps have been based on measurements gathered from field surveys, and extrapolated using aerial photograph interpretation and ecological modeling (similar to growth and yield modeling) (Arroyo et al. 2008). Field surveys provide excellent data because researchers can evaluate physical details of fuels on site, but their use is often limited because they are time consuming, costly, and the variability of fuels is not captured when extrapolated to larger scales (Arroyo et al. 2008). Aerial photograph interpretation provides a compromise between cost and quality, so it can be used over large areas to provide reasonable fuel estimates (Arroyo et al. 2008). However, unlike Lidar, it is unable to measure the vertical structure or subcanopy structure of forests (Arroyo et al. 2008). Ground truthing with field surveys is still required to validate data, but Lidar is able to reconstruct the three-dimensional structure of forested landscapes—a characteristic that my lead to considerable improvements in fuel mapping (Arroyo et al. 2008).

Fuel types are characterized by a number of fuel metrics, which are often confused. Some of the common terms used to describe fuels and fuel metrics relevant to determining fuel type are summarized in Table 3.

Table 3: Glossary of fire science terminology. Definitions are based largely on information found in Erdody and Moskal (2010), Arroyo et al. (2008), Scott and Reinhardt (2007), and Riaño et al. (2003).

Fuel Metric	Definition
available canopy fuel	The foliage and fine branchwood of trees which is able to sustain crown fire.
canopy cover	The fraction of ground area covered by the vertical projection of tree crown perimeters.
canopy height	The highest height at which there is sufficient canopy fuel to sustain crown fire.
canopy base height	The lowest height above the ground above at which there is sufficient canopy fuel to propagate a fire vertically.
canopy bulk density	The mass of available canopy fuel per unit volume. A measure of foliage biomass divided by crown volume.
crown fire	A wildland fire that burns forest canopy fuel.
decision support systems	Software or programs such as FARSITE and BEHAVE that are comprised of mathematical fire models capable of predicting fire behaviour and rate of spread.
crown volume	Crown area after correction for mean canopy cover times the distance between canopy height and canopy base height.
fire model	Mathematical relationships that describe the potential characteristics of a fire. Often informally referred to as fire behavior models, fire effects models, and smoke models. Fire models are the foundation of decision support systems such as FARSITE and BEHAVE.
foliage biomass	A percentage of the total tree biomass related to foliage.
fuel map	A visual representation of the spatial distribution of fuel types.
fuel type	An identifiable association of fuel elements of distinctive species, form, size, arrangement, and continuity that will exhibit characteristic fire behavior under defined burning conditions.
horizontal continuity	A physical property of the distribution of fuels on a horizontal plane that affects the rate and direction of spread.
ladder fuel	Fuel that provides vertical continuity between surface and canopy fuels, increasing the likelihood that fire will carry from surface fuel into the crowns of shrubs and trees.
surface fire	A fire that spreads through surface fuel without consuming any overlying canopy fuel.
surface fuel	Fuel lying on or near the surface of the ground, consisting of leaf and needle litter, dead branch material, downed logs, bark, tree cones, and living plants of low stature.
vertical continuity	A physical property based on the vertical arrangement of fuel that influences rate and direction of spread in the vertical dimension.

Fuel maps can be developed using Lidar because it is able to measure various physical properties of fuels including size, quantity, and arrangement (Morsdorf et al. 2004). Lidar can quantify several different metrics of crown and surface fuels including: crown bulk density, foliage biomass, crown volume, crown base height, canopy height, available canopy fuel, understory height, percent canopy cover, surface area-to-volume ratio, vertical continuity, ladder fuels, horizontal continuity, and size class of fuel elements (Erdody and Moskal 2010, Riaño et al. 2003). Figure 5 illustrates the main canopy fuel metrics. Canopy bulk density is an important metric because decision support systems such as FARSITE use a minimum canopy bulk density value to determine when active crown fire can be sustained

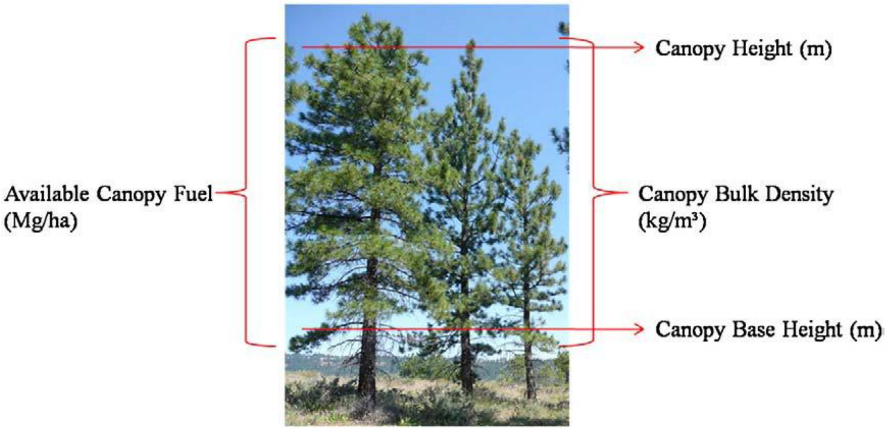

Figure 5: Canopy fuel metrics (Erdody and Moskal 2010).

(Erdody and Moskal 2010). In addition, available crown fuel is commonly used in the First Order Fire Effects Model (FOFEM) to determine the proportion of the crown that might be consumed in a wildfire (Reinhardt 1997, 2006 in Erdody and Moskal 2010). These metrics form the basis of fuel maps, which can be used as direct inputs into decision support systems (Mutlu et al. 2008).

Tree heights and vertical forest structure can be measured with a high level of accuracy using airborne Lidar (Andersen et al. 2005, Means et al. 2000).This is significant because the vertical continuity of fuels is a major determinant in the ability for a surface fire to become an aggressive and fast-spreading crown fire (Skowronski et al. 2007). Tree heights are determined by subtracting the ground elevation from the elevations of the first laser pulse returns, which are reflected off the upper levels of the canopy (Means et al. 2000). This is illustrated in Figure 6. Similarly, the height of subcanopy and understory vegetation can be determined. Lidar data can be sorted into different height bins (i.e. <1 m, 1-2 m, 2-3 m,>3 m), which are used to assess surface fuels, ladder fuels, and canopy base height (Skowronski et al. 2007). For example, an absence of fuels in the first three height bins (<1m-3m) would indicate that ladder fuels were not present, whereas multiple returns in each height bin would show vertical fuel continuity. Tree heights can also be used to estimate basal area and volume using regression, based on the strong empirical relationships between basal area and height for some species (Means et al. 2000, Skowronski et al. 2007).

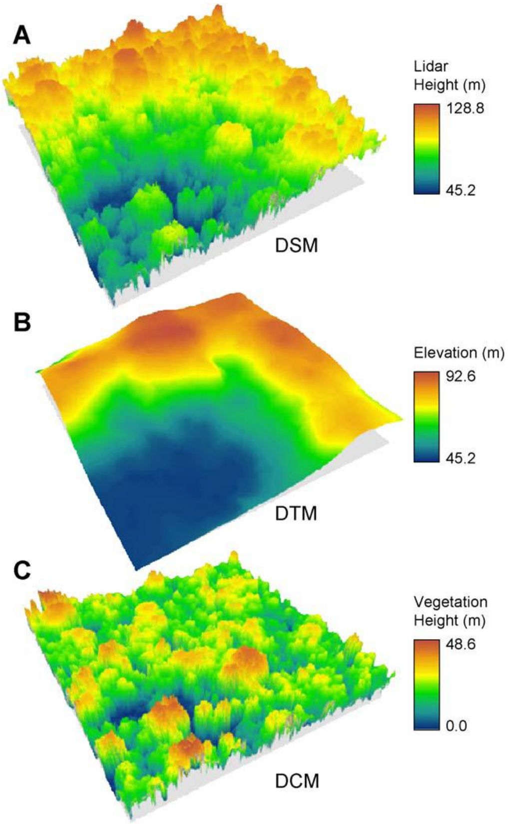

Figure 6: The digital surface model (A) shows the true elevation of the top of the canopy, the digital terrain model (B) shows the underlying surface elevation, and the digital canopy model (C) shows vegetation and tree heights. The digital canopy model (C) is created when the DTM (B) is subtracted from the DSM (A) (Clark et al. 2004).

The ability to map the horizontal distribution of fuels below the canopy is a unique feature that makes Lidar well suited to fuel mapping. Traditionally, remote sensing imagery and aerial photographs have been used to develop fuel maps but they lacked the ability to see through the canopy and represent the forest in three dimensions (Erdody and Moskal 2010). Lidar pulses are able to penetrate the canopy and provide information on the spatial distribution and arrangement of surface fuels and ladder fuels (Riaño et al. 2003). Direct measures of coarse woody debris (CWD) can be obtained from Lidar based on a direct correlation with surface roughness, and fuels can be estimated across a continuum (Seielstad and Queen 2003). This data is extremely valuable to fire managers because fire growth is often determined by the uniformity and continuity of fuels. The ability to quantify fuel volumes beneath a closed canopy and map fuels along a continuum rather than in discrete classes is unprecedented in fuel mapping and supports the potential of Lidar in fuel assessments (Seielstad and Queen 2003).

Lidar-derived fuel maps are robust and research suggests that they result in better predictions of fire intensity and rate of spread than traditional fuel maps (Andersen et al. 2005) because the quality of the model input is better (Mutlu et al. 2008). According to Mutlu et al. (2008), many fire mangers do not have access to local fuel maps capable of running decision support systems such as FARSITE. Fuel maps are necessary to power decision support systems and accurate inputs produce outputs that are better able to help fire managers allocate resources based on the predicted rate and direction of spread (Mutlu et al. 2008). Improved outputs can result in better decision making and efficiencies that save thousands of dollars despite the cost of Lidar acquisition and processing (Mutlu et al. 2008). When comparing the three-dimensional Lidar-derived fuel maps to Quickbird-derived fuel maps developed from two-dimensional satellite imagery, Mutlu *et al.*(2008) found that fire growth area results and fire perimeter results were improved by at least 13% using Lidar, and fire characteristics were predicted in greater detail. Ultimately, improved fuel maps and predictions of fire behaviour may result in cost savings when suppressing fires that would quickly pay off the costs of the Lidar dataset.

In addition to improving data quality, Lidar can also increase the efficiency of collecting fuels data for fire behaviour modelling. Lidar is convenient because the output data can be used as a direct input to decision support systems (Andersen et al. 2005, Riaño et al. 2003). This gives Lidar an advantage over traditional methods for quantifying fuels. Aerial photograph interpretation and ground sampling require much more effort to yield data compatible with fire behaviour programs because laboratory or field analyses are required and a human being has to enter the information into the computer (Riaño et al. 2003). In contrast, Lidar data can easily be linked to geographic information systems (GIS) and entered into decision support systems through computer processing. A drawback of this is that datasets are large (approximately 400MB of data per km^2) and data processing can be slow (Morsdorf et al. 2004). Nevertheless, FARSITE and other decision support systems are dependent on spatial information (Mutlu et al. 2008) and Lidar is able to provide a very high quality input three times as fast as traditional methods and at half the cost (Means et al. 2000).

Taking advantage of the accuracy and efficiency of Lidar, new fuel metrics could be developed using previously unattainable measurements such as aerodynamic roughness length (Lefsky et al. 2002). Aerodynamic roughness length is the height at which the wind speed becomes zero in a forest canopy (Lefsky et al. 2002). The integration of airflow modeling could further improve the estimates of decision support systems such as FARSITE. In addition, new ways of describing canopy structure such as the canopy volume method (CVM) which represents forest structure through the use of voxels (three-dimensional pixels) could be used to present new visualizations of vegetation layers and improved estimates of forest structure. In light of the speed at which Lidar data can be acquired and processed, a little creativity might lead to the development of a useful new metric which was previously too time-consuming or costly to obtain.

HOW COULD LIDAR BE USED IN BRITISH COLUMBIA?

FIRE MANAGEMENT PLANNING

Fire management planning could be improved by using Lidar to help prioritize and evaluate fuel management treatments and prescribed burning. Recent use of Lidar in the United States has shown that Lidar-derived fuel maps can be used by managers to identify areas of dense fuel accumulations (Skowronski et al. 2007). It has also shown that when overlain on other GIS layers, Lidar-derived fuel maps can be extremely useful in determining the location of fuel management treatments and prescribed burns (Skowronski et al. 2007). As the province strives to shift from a reactive to a proactive management style, which includes more prescribed fire and fuel management (Forest Practices Board 2012), the integration of Lidar-derived fuel maps could assist in decision making regarding treatment location and offer a quantifiable means of measuring the effectiveness of treatments.

Lidar-derived fuel maps could also be useful when developing fire management plans. One of the key objectives of these plans is to identify areas where fire is wanted, not wanted, or not wanted under certain conditions (Forest Practices Board 2012). Several factors are used to determine where fire might be wanted including: fuel type, communities and infrastructure, land ownership and tenure, land cover, wildlife habitat, and others (Forest Practices Board 2012). While fuel type is just one of the factors contributing to this decision, it is an important factor and the current qualitative methods of determining fuel type leaves room for inconsistency in developing a plan. Quantifiable, spatially explicit measurements presented as fuel maps could help to improve the transparency of decision making.

FIRE ANALYSIS

It is critical to have good estimates of fire growth because the location and size of a fire determine the values at risk, cost of suppression, and probability of successful fire control. These factors are critical components of fire analyses, which guide management decisions and suppression strategies and tactics (Forest Practices Board 2012). Without good estimates of fire spread, it is impossible to make consistent and accurate decisions with regards to fire management.

British Columbia needs to improve its fire growth analyses so that information is available to managers when they need it. The February 2012 Forest Practices Board special investigation found that 62% of fire analyses did not include a required fire growth analysis (Forest Practices Board 2012). When critical information is unavailable, incident commanders are forced to make strategic decisions based on their experience and the best available information (Forest Practices Board 2012). This forces them to make ad hoc decisions that lack the consistency and accuracy intended by policy and that influence the provincial prioritization of fire suppression efforts and spending of public funds (Forest Practices Board 2012). The Forest Practices Board has recommended that the Wildfire Management Branch adopt an automated system of fire growth prediction because fire behaviour specialists are usually not available within the required time frame to properly support management decisions required for individual fires

(Forest Practices Board 2012). Moving to an automated system would help to ensure that fire growth predictions are consistent and available when needed (Forest Practices Board 2012).

As discussed in previous sections, Lidar can be used to produce highly accurate digital terrain models and fuel maps, which could be used to improve fire growth prediction in British Columbia. Research in the United States has shown that Lidar could potentially save millions of dollars in wildfire management by providing more accurate inputs to decision support systems so that variables like rate of spread and fire intensity could be predicted more accurately and used to guide tactics in fire suppression (Andersen et al. 2005). Integrating Lidar data to improve fire growth models could be an excellent way for the Wildfire Management Branch to work towards their objective of leading the world in sustainable environmental management.

Furthermore, Lidar-derived fuel maps could help to reduce fire suppression costs by providing baseline information supporting decisions to monitor fires rather than actively suppress them. The Forest Practices Board found that managers are scared to apply minimal resources or simply monitor fires because of liability; they consider it risky from personal and professional perspectives (Forest Practices Board 2012). This kind of risk-avoidance can greatly increase the cost of fire suppression (Forest Practices Board 2012). Use of Lidar-derived fuel maps would enable fire managers to make informed decisions and demonstrate due diligence in two ways. First, since Lidar measurements are quantitative and the resulting fuel maps are accurate over a range of spatial scales, managers will be in a better position to assess fire hazard. Secondly, the fuel maps can be used in fire growth models to evaluate potential rates of fire spread in order to make informed and defendable decisions. Managers might be more comfortable to choose monitoring rather than suppression as the best management action if they had concrete, quantifiable measurements to support their decisions.

IMPLEMENTATION

Although initially expensive, support of proactive management and innovation can yield long-term benefits. Lidar data is costly to acquire and process, so it would be difficult to implement for the entire province; however, it could be very practical to start by targeting the wildland-urban interface. There are three main reasons for this: (1) these areas are more likely to have existing Lidar data, (2) fuel types are highly variable and fine-scale detail would be helpful for prioritizing fuel management treatments and fire suppression objectives, and (3) the high risk and consequence for wildfires in the wildland-urban interface make fire management important.

The Forest Practices Board has recommended that the Wildfire Management Branch use ‘Fireview’ to share mapping information digitally in the province (Forest Practices Board 2012). Fireview a user-friendly, internet-based, program that was designed to make it easy for Wildfire Management Branch staff to view and print maps and images (Forest Practices Board 2012). It is currently underutilized, but geomatics staff believe that “Fireview could offer an effective solution to mapping issues if it was supported, promoted, and made a priority” (Forest Practices Board 2012). Some investment would be required to get this program up and running. A greater investment might be required to include Lidar-derived fuel mapping. Nonetheless, as the Wildfire Management Branch is still considering what information should be included in the program, this would be a good time to be forward thinking and ensure that Fireview could integrate Lidar DTMs and fuel maps. Fireview could be a good way to incorporate Lidar data with other important fire management information such as wildlife habitat, property ownership, and infrastructure in a way that would be useful to fire managers.

CONCLUSION

Integrating Lidar in British Columbia could be very beneficial. Lidar provides many opportunities to improve measurements of forest fuels and guide fire management decisions. It is a highly accurate type of remote sensing that can measure the three-dimensional structure of forests in a quantifiable manner producing estimates of surface, ladder, and canopy fuels. Lidar can be expensive to acquire and process, but relative to traditional methods of fuel mapping, which require significant human effort, its cost is reasonable (Means et al. 2000). It provides an opportunity to cover large areas very quickly and the benefits of improved fire management planning, fire growth prediction, and decision making could lead to a decreased pressure on public funds.

Lidar provides several high-quality inputs for decision support systems including slope, aspect, elevation and fuel type and it is capable of more. Broader investigations of Lidar applications have shown that it is effective in mapping active fire characteristics and post-fire ecological effects including fire intensity, fire severity, erosion and sedimentation (Lentile et al. 2006). There is also potential to develop new fuel metrics and improve fire models (Lefsky et al. 2002). Furthermore, Lidar data is much more versatile than other fuel-type data and could serve multiple functions for its cost. For example, it could be shared with the Ministry of Forest, Lands, and Natural Resource Operations to improve their vegetation resources inventory and provide special assistance in assessing critical hydrological areas and wildlife habitats.

The widespread availability of Lidar data comes at a time when there are multiple forces—both internal and external—pushing the Wildfire Management Branch towards global excellence. Their goal is to lead the world in sustainable forest management, and the public is urging them to protect their homes, assets, wildlife, water, and the aesthetics of our Province. The Forest Practices Board review is demanding an emphasis on proactive management and Lidar is an innovative technology that is available to meet many of the demands of improved fire management planning and fire suppression. As with all technologies, it will be very important to find a way for managers to actually access and take advantage of the information that is available. Fireview may be able to fill this need, or another mechanism may be required. Further research should be done on how to best implement and integrate Lidar data in order to take advantage of this opportunity to move forward.

REFERENCES

Andersen, H., McGaughey, R.J., and Reutebuch, S.E. 2005. Estimating forest canopy fuel parameters using LIDAR data. Remote Sens. Environ. 94: 441-449.

Arroyo, L.A., Pascual, C., and Manzanera, J.A. 2008. Fire models and methods to map fuel types: The role of remote sensing. For. Ecol. Manage. 256: 1239-1252.

Bater, C.W., and Coops, N.C. 2009. Evaluating error associated with lidar-derived DEM interpolation. Computers and Geosciences 35: 289-300.

Clark, M.L., Clark, D.B., and Roberts, D.A. 2004. Small-footprint lidar estimation of sub-canopy elevation and tree height in a tropical rain forest landscape. Remote Sens. Environ. 91: 68-89.

Erdody, T.L., and Moskal, L.M. 2010. Fusion of LiDAR and imagery for estimating forest canopy fuels. Remote Sens. Environ. 114: 725-737.

Forest Practices Board. 2012. Fire Management Planning: Special Investigation. Forest Practices Board, Rep. 34.

Forest Practices Board. 2010. Managing Forest Fuels in the Wildland Urban Interface. Forest Practices Board, Rep. 28.

Krabill, W., Frederick, E., Manizade, S., Martin, C., Sonntag, J., Swift, R., Thomas, R., Wright, W., and Yungel, J. 1999. Rapid Thinning of Parts of the Southern Greenland Ice Sheet. Science 283: pp. 1522-1524.

Krabill, W., Wright, C., Swift, R., Frederick, E., Manizade, S., Yungel, J., Martin, C., Sonntag, J., Duffy, M., Hulslander, W., and Brock, J. 2000. Airborne laser mapping of Assateague National Seashore beach. Photogramm. Eng. Remote Sensing 66: 65-71.

Lefsky, M.A., Cohen, W.B., Parker, G.G., and Harding, D.J. 2002. Lidar Remote Sensing for Ecosystem Studies. Bioscience 52: 19-30.

Lentile, L., Holden, Z., Smith, A.S., Falkowski, M., Hudak, A., Morgan, P., Lewis, S., Gessler, P., and Benson, N. 2006. Remote sensing techniques to assess active fire characteristics and post-fire effects. IJWF 15: 319-345.

Means, J., Acker, S., Fitt, B., Renslow, M., Emerson, L., and Hendrix, C. 2000. Predicting forest stand characteristics with airborne scanning lidar. Photogramm. Eng. Remote Sensing 66: 1367-1371.

Morsdorf, F., Meier, E., Kötz, B., Itten, K.I., Dobbertin, M., and Allgöwer, B. 2004. LIDAR-based geometric reconstruction of boreal type forest stands at single tree level for forest and wildland fire management. Remote Sens. Environ. 92: 353-362.

Mutlu, M., Popescu, S.C., and Zhao, K. 2008. Sensitivity analysis of fire behavior modeling with LIDAR-derived surface fuel maps. For. Ecol. Manage. 256: 289-294.

Province of British Columbia. 2010. Wildland Fire Management Strategy: Acheiving Global Excellence in Fire Management. Province of British Columbia,

Riaño, D., Meier, E., Allgöwer, B., Chuvieco, E., and Ustin, S.L. 2003. Modeling airborne laser scanning data for the spatial generation of critical forest parameters in fire behavior modeling. Remote Sens. Environ. 86: 177-186.

Scott, J. H. and E.D. Reinhardt, compilers. 2007. FireWords Version 1.0: Fire Science Glossary [electronic]. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory (Producer). Available: http://www.fs.fed.us/fmi

Seielstad, C., and Queen, L. 2003. Using airborne laser altimetry to determine fuel models for estimating fire behavior. J. For. 101: 10-15.

Shuckman, K., and Renslow, M. 2007. Characteristics of Lidar Data. Pennsylvania State University Department of Geography.

Skowronski, N., Clark, K., Nelson, R., Hom, J., and Patterson, M. 2007. Remotely sensed measurements of forest structure and fuel loads in the Pinelands of New Jersey. Remote Sens. Environ. 108: 123-129.

USDA Forest Service Remote Sensing Applications Center. 2009. 2012:

Wildfire Management Branch. 2011. Fighting Wildfire. 2012:

Wulder, M., Bater, C., Coops, N., Hilker, T., and White, J. 2008. The role of LiDAR in sustainable forest management. The Forestry Chronicle 84: 807-826.