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USING LIDAR FOR FOREST AND FUEL STRUCTURE MAPPING: OPTIONS, BENEFITS, REQUIREMENTS AND COSTS

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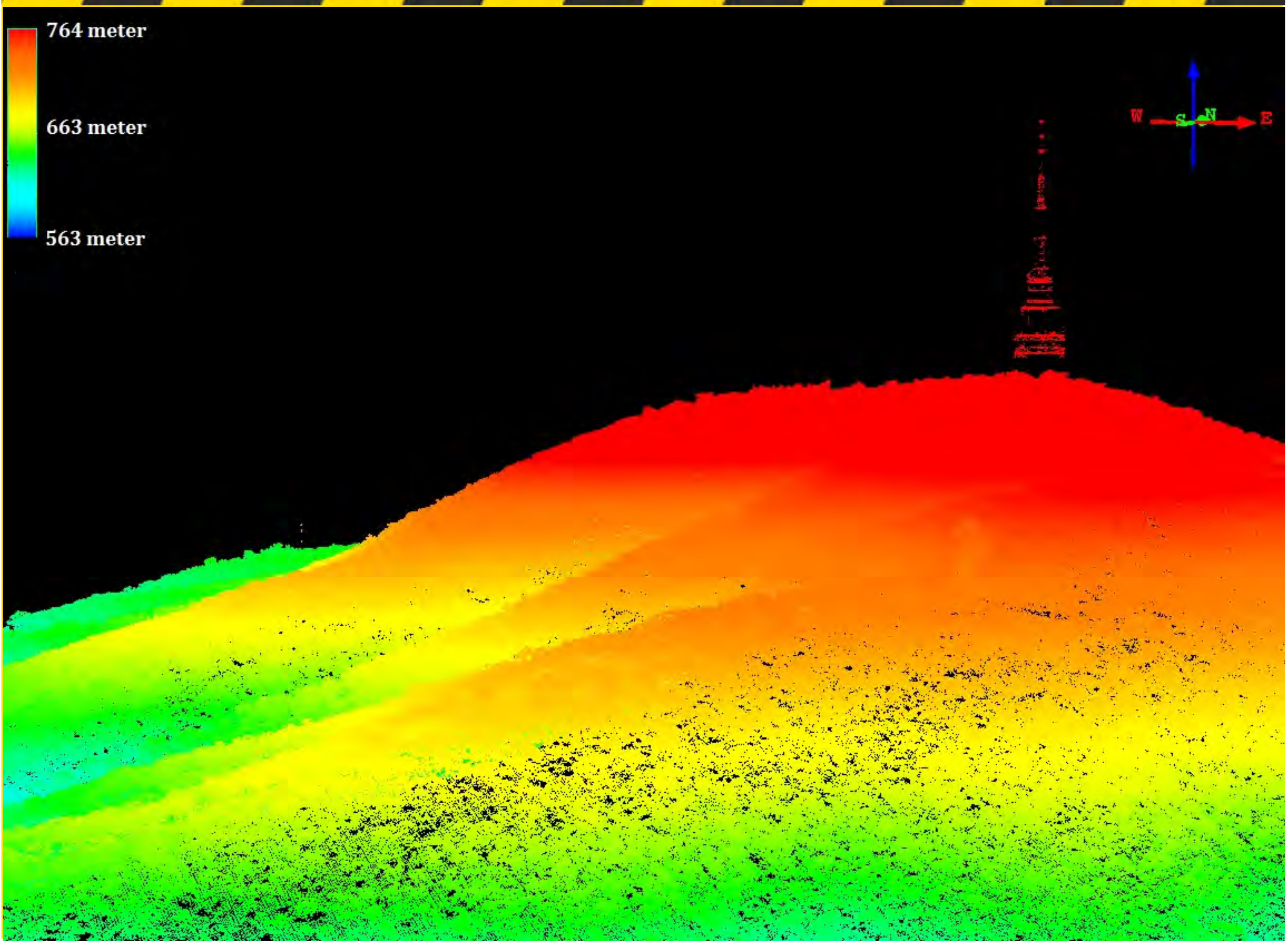


Version	Release history	Date
1.0	Initial release of document	16/03/2015

Publisher: Bushfire and Natural Hazards CRC, East Melbourne, Victoria.

Cover: A LiDAR image.

Citation: Yebra M, Marselis S, van Dijk A, Cary G and Chen Y (2015) Using LiDAR for forest and fuel structure mapping: options, benefits, requirements and costs, Bushfire & Natural Hazards CRC, Australia.

Foreword

Understanding fuel structure is important for assessing suppression difficulty, risk of damage from bushfires, monitoring fuel build up and planning hazard reduction programs. Technologies such as airborne Light Detection and Ranging (LiDAR) can provide precise information about fuel structure over larger areas. However, the use of LiDAR by fire managers is still in the early stages and has not been implemented through any routine operational program in Australia.

This report aims to address this situation by describing and evaluating the maturity and suitability of airborne LiDAR to derive the different types of information needed in forest fuel assessment. It does so through a set of questions scoped in consultation with fire managers through the Bushfire and Natural Hazards CRC project 'Mapping bushfire hazard and impacts'. The language and technical detail is aimed at a wide audience with fields of expertise outside LiDAR.

This report first covers some of the basic principles on LiDAR and then focuses on the analysis of the information content and accuracy of airborne LiDAR to retrieve the forest fuel attributes that are important for fire management. The information that can be derived about the height, cover fraction and density of different over- and understorey layers is assessed, along with other useful information that may be derived. Additional measurements that help to make more optimal use of airborne LiDAR data are presented, including terrestrial laser scanning, UAV-borne LiDAR, and airborne imaging. Guidance is provided on discovering existing LiDAR data, factors determining the cost of new LiDAR data acquisition, and options for processing the data. Finally, the current and future development in the use of LiDAR for fire management are discussed.

Summarising, airborne LiDAR may be considered a mature data product that is commercially available, using established data standards. However, standardised data specifications and processing methods for applications in fuel mapping do not yet exist. Essential aspects to consider are the type of fuel information, accuracy and spatial detail desired. Greater data density can increase accuracy and spatial detail, but will also increase the cost of acquisition. In forests with a dense overstorey canopy high data density may be the only way to obtain information on the understorey. In small-scale applications, field or UAV-mounted LiDAR systems may be a suitable alternative for airborne LiDAR.

Priority areas for research and development to achieve more cost-effective and successful use of LiDAR by the fire management community were identified. This includes the development of standardised methods to acquire and process airborne LiDAR data for fuel mapping, the validation of these methods using field measurements, and investigation of full-waveform airborne LiDAR as a promising alternative to current LiDAR data collection methods. The Bushfire and Natural Hazards CRC project 'Mapping bushfire hazard and impacts' is working with end users to pursue each of these lines of enquiry.

Acknowledgements

This report was made possible through funding from the Bushfire and Natural Hazards CRC through the project 'Mapping bushfire hazard and impacts' (project A1, Milestone 1a - Analysis of the information content and accuracy of airborne LiDAR and opportunities to reduce the cost of data processing and information extraction). We thank the project end users for their contribution to determining the scope of this report.

The airborne LiDAR data used in this report was collected with funding from ACT Parks and Conservation, The Terrestrial Ecosystem Research Network (TERN), the CSIRO Earth Observation Informatics Transformational Capability Platform, and a CSIRO Payne-Scott Award.

The field LiDAR data was collected in collaboration with Tom Jovanovic (CSIRO) and Michael Schaefer (CSIRO-TERN AusCover). Philip Zylstra and colleagues (Wollongong University) greatly contributed to measure fuel structural parameters in the field.

Contents

1. Basics of airborne LiDAR data collection

LiDAR is the acronym for 'light detection and ranging'. LiDAR scanners can be ground-based, airborne or spaceborne. They generate three-dimensional (3D) models of a target by emitting pulses of light and precisely timing their reflections from the target (Figure 1). This timing information is used to create a point cloud, a set of possibly millions of 3D coordinates that represent targets that were hit.

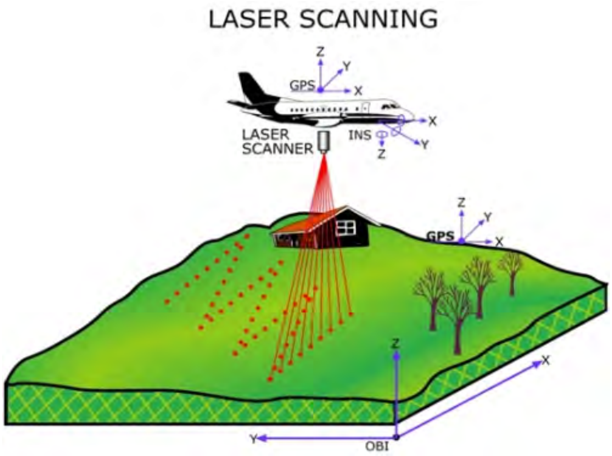


Figure 1. To determine the precise location (that is, georeference) of LiDAR points, use is made of global positioning systems (GPS) to derive the position of the aircraft, a so-called inertial navigator that determine the pointing direction of the sensor, and the LiDAR range to extrapolate the coordinates of a target point on the ground (source: ASPRS).

The laser pulse is a beam of light comprising a continuous waveform, that is, its wavelength and intensity are kept constant. The beam footprint is the area on the ground that the LiDAR sensor collects information from.

The recorded return signal is the result of the interaction of the laser beam with one or more objects and usually referred to as the (full) waveform. When LiDAR systems for mapping were first developed for commercial purposes, LiDAR sensors were not electronically capable of recording the full-waveform in the return signal from a small footprint (high spatial resolution). Therefore a filter was applied to detect peaks in the reflected waveform and to record the timing of those peaks as discrete "returns". A peak is generated from a reflection caused by the top of the vegetation, but a sufficient amount of laser light energy is able to continue on to generate returns from lower portions of the vegetation, and finally, from the ground. Very early LiDAR systems recorded only one discrete return, that is, either the first peak or the recorded signal of the reflected wave. By around the year 2000, commercial systems became capable of measuring multiple returns per pulse. These multiple returns can be analysed and classified to produce information about objects above the ground as well as the bare ground surface. A depiction of multiple returns from open vegetation that are classified into different vegetation and bare ground classes can be seen in Figure 2.

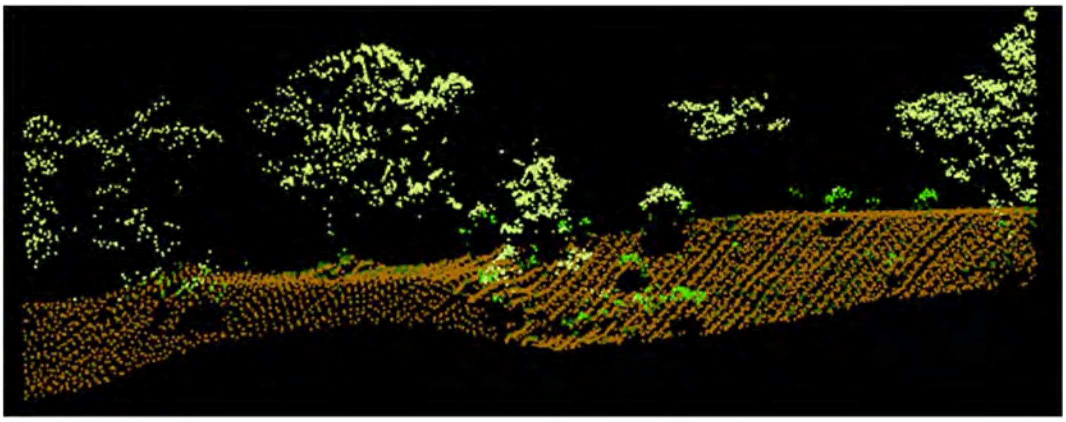


Figure 2. Visualization of multiple LiDAR returns at Black Mountain reserve, Australian Capital Territory. Brown = ground returns, pale green = trees, light and dark green = low vegetation/shrubs Source [1].

The more returns recorded, the larger the resulting dataset becomes and the greater the likelihood of having more returns that capture information about the understorey , provided the canopy is not so dense that it blocks the laser pulse. LiDAR datasets tend to be very large, due simply to the high number of emitted pulses per area. Added to that, there are multiple returns per emitted pulse, causing the overall size of the dataset to grow geometrically. Early multiple return systems were designed to record up to 5 return pulses, but analysis of datasets showed that, in practice, 4th and 5th returns almost never occurred. Most LiDAR systems designed today for topographic mapping are optimized to record 3 return pulses. Consequently higher point densities per unit area can only be achieved by overlapping different flight lines, that is, flying the same area more than once.

However, there are systems that have the option for full-waveform recording, that is, the signal is not summarised into separate point returns, but the entire return signal is recorded in a large footprint (low spatial resolution) (Figure 3). Since 2004, these new so-called full-waveform small footprint LiDAR systems are available.

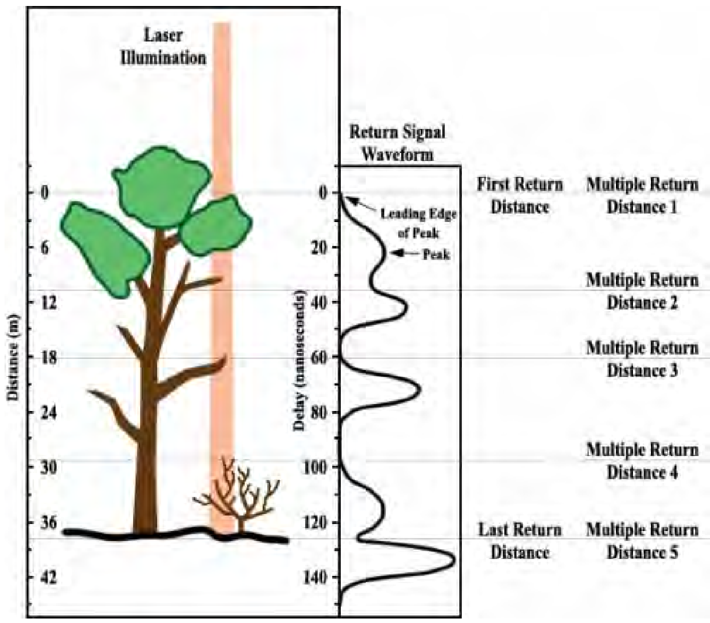


Figure 3. Full-wave LiDAR vs discrete multiple-return LiDAR. In full-waveform LiDAR, the entire return pulse is digitized and recorded. In a discrete multiple-return LiDAR, only the peaks are recorded. Source: ASPRS.

Capturing and recording this vast amount of data poses both challenges and opportunities. A challenge using full-waveform data is that data processing load increases at about 30 to 60 times when compared to multiple return LiDAR. Furthermore, there is currently little commercial software devoted to the automated processing of full-waveform data over large areas. However, there are some very promising opportunities for bushfire management presented by full-waveform technology mostly in the analysis of vegetation density, mapping live versus dead vegetation, forest fuel analysis, and wildlife habitat mapping.

2. Forest fuel attributes important for fire management

Fuel assessment is an important activity in understanding suppression difficulty, assessing risk of damage from bushfires, monitoring fuel build up and planning hazard reduction programs. Fuel assessment is a complex activity. Fuel exists in a variety of forms and arrangements. They can be fine (< 6mm in any one dimension), or coarse, dead or live, woody or non-woody. Understorey fuels include duff, surface litter leaves and twigs, downed dead wood, near-surface (suspended litter, herbaceous, and low shrubs) and elevated (shrubs) fuel. Canopy and bark fuel includes tree foliage and bark of intermediate and overstorey trees (Figure 4). Fuel characteristics including quantity of various fuel components by size class, live and dead fraction, horizontal and vertical continuity, density and packing ratio and other fuel attributes are important in determining the rate of spread and intensity of bushfires [2].

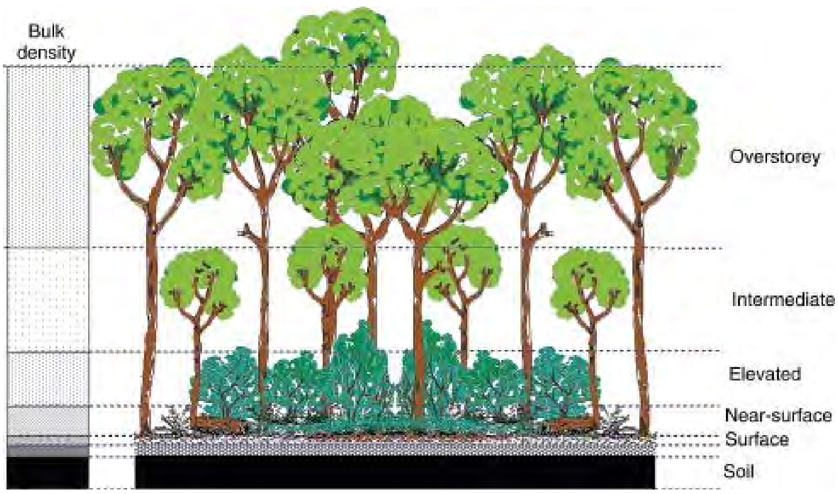


Figure 4: Indication of different forest layers used in forest fuel assessments [3]

For example, several fire and management agencies adopted the Victorian visual fuel assessment system in dry eucalypt forests [4]. The objective of this system is to assign a hazard rating to a specific patch of forest. This rating indicates a measure of the difficulty of fire suppression and therefore is related to the fire risk at that specific area. The overall fuel hazard rating depends on the presence and state of different vegetation layers: surface, near-surface, elevated and bark. The Project Vesta fuel hazard scoring system is similar to the Victorian system, with the difference that the scale that underlies the scoring relates more directly to fire behaviour [5].

Table 1 lists related land cover types for existing fire behaviour models in Australia, as well as other 'fuel attributes', being the fundamental physical properties of the fuel that affect fire behavior [6]. Some of these are not included in any of the existing fire behaviour models, either used directly or through surrogate variables, while others are fundamental to new generation fire behaviour models. For example, surface fuel hazard score or rating, near-surface fuel hazard score or rating, and near surface fuel height are essential for predicting rate of spread in dry eucalypt forests of southern Australia [7]. Canopy structural properties of a stand (for example, canopy height, base height, cover and bulk density) are essential inputs of fire behaviour models and systems designed to predict crown fire behaviour [8]. Canopy cover is a significant variable on modelling rate of fire spread in crown fires while canopy height for surface fires in a Mallee-heath shrubland [9].

Table 1. Fuel parameters and attributes requirements for the main Australian fire behaviour models. Simplified from [6]

Land cover type	Fuel strata	Fuel parameter/attribute
Forest	Surface	Duff Fuel Load Fine Fuel Load Woody Fuel load Hazard score/rating Height Fuel continuity Fuel particle size
	Near-surface	Fuel Load Hazard score/rating Cover Height
	Elevated	Fuel Load Hazard score/rating Height
	Bark	Load Hazard score/rating Strength or attachment
	Canopy/overstorey	Fuel Load Height Base height Bulk density Fuel continuity
Grassland	-	Fuel Load Curing Fuel age (structure) Ratio of live/dead
Shrubland/Mallee/Heath	-	Shrub Height Tree height NS hazard rating EL hazard rating Fuel continuity Ratio of live/dead

Accurate quantification of fuel parameters and attributes is critical to improving fire danger assessment and fire behaviour modelling. The traditional method of fuel assessment involves field surveying using a combination of qualitative (visual) and quantitative (destructive) sampling methods. Although these methods can be effective, they are very labour intensive and spatially severely limited by time, resources and accessibility. Some empirical methods have being developed to track fuel dynamics (i.e. fuel accumulation models with time since fire [3]) but present similar limitations. The use of airborne or other remote sensing data for fuel mapping can help to overcome these disadvantages, if larger areas can be mapped on the basis of the remote sensing classification system.

3. What can airborne LiDAR tell us about forest fuel attributes?

LiDAR technology, in its various forms, provides an accurate and efficient mean of estimating and monitoring most of the required information on fuel parameters and attributes listed in Table 1, as it records both the location and density of fuel components. At present, the main limitations of airborne LiDAR are related to the weakening laser pulse strength as it penetrates through the canopy towards the ground level and then back up towards the sensor. This is especially an issue in dense forest canopies, in which fuel parameters near the top of the canopy (for example, canopy height) are predicted with better accuracy than metrics near mid-canopy (for example, shrub height) or with even lower accuracy, near-ground level metrics (for example, fine litter cover). Full-waveform LiDAR provides more detailed vertical structure of the canopy and understorey but has its own technical challenges. Consequently, the information that can be extracted from LiDAR depends on the type of LiDAR selected and this is discussed below.

Canopy fuel

LiDAR directly measures tree **canopy height** with an accuracy comparable to field canopy height measurements. On average, LiDAR tends to slightly underestimate individual canopy height because of the low probability that the small-footprint laser pulses will intercept the apex of the tree top (Figure 5, [10]).

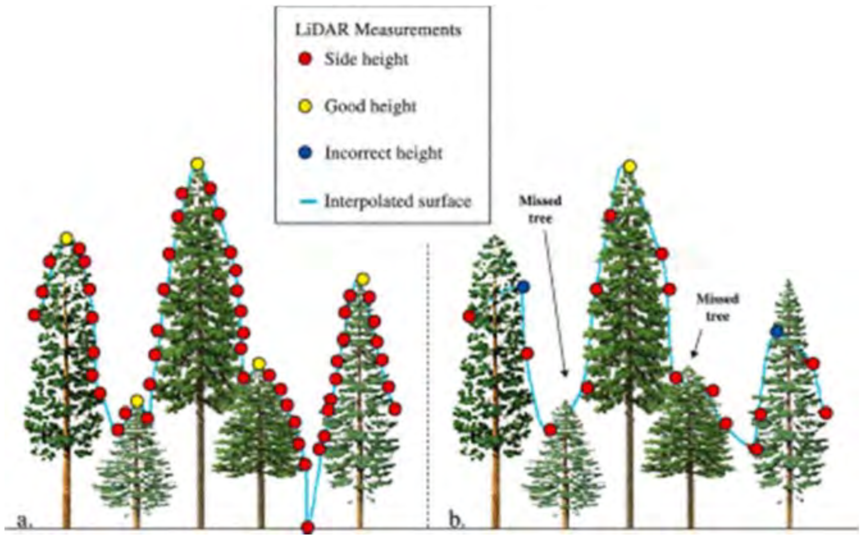


Figure 5. (a) Accurate estimate of tree height dispersion due to a high point density. (b) Less accurate estimate of tree height dispersion due to low point density (source [10]). Higher point density yields better accuracy in detecting the dispersion of tree heights.

Figure 6 shows a map of canopy height for mixed pasture and open woodland derived from multiple return discrete LiDAR (>5 pulses per square metre, or pl m^{-2}) and a comparison against field measurements carried out with a handheld laser ranger for 28 trees. LiDAR derived canopy height corresponds very well with the field measured canopy height but as expected the LiDAR canopy height is slightly lower than the field measured canopy height. The accuracy of tree height estimation will normally be sufficient for vegetation mapping exercises. A canopy height map as such as shown in Figure 6 can be used reliably as an input in crown fire behaviour models (Cruz et al 2008).

a)

b)

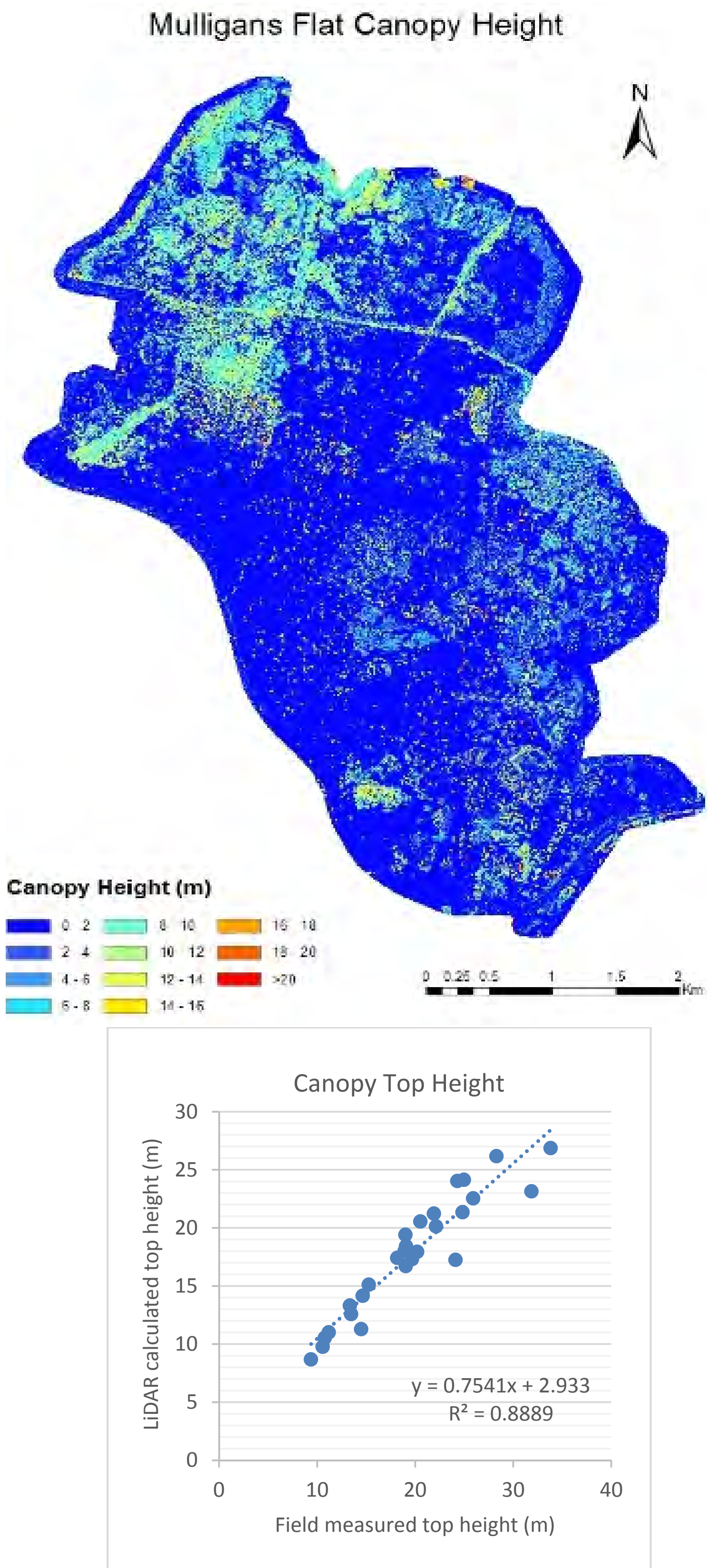
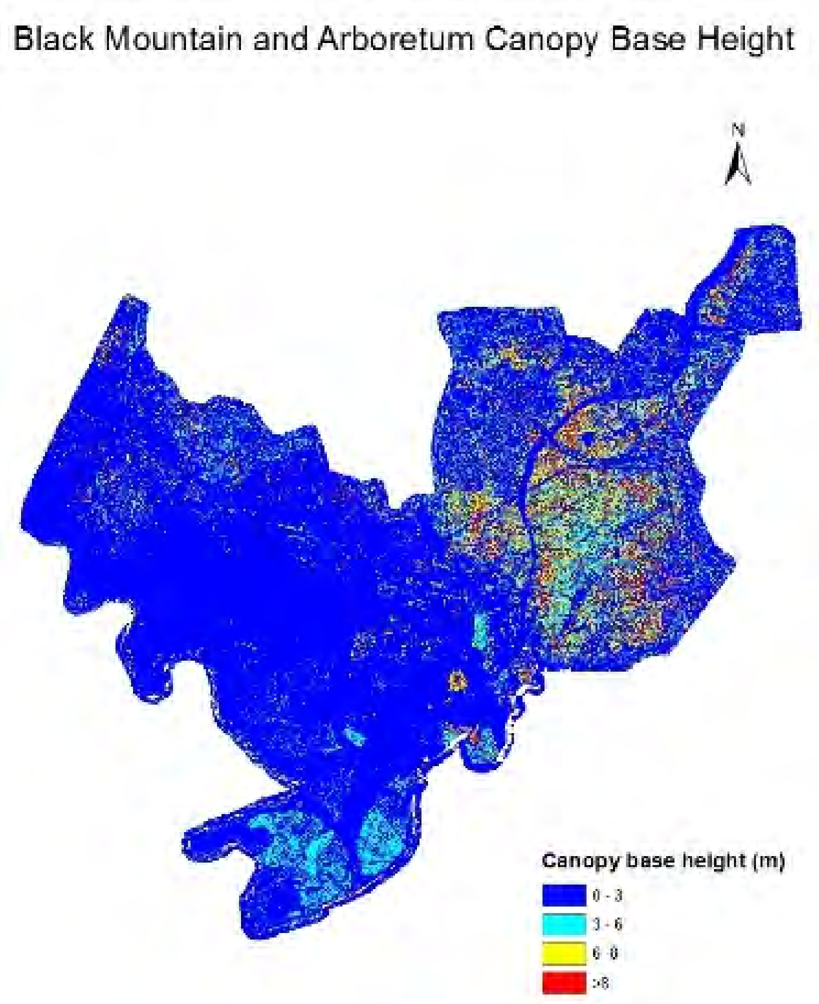


Figure 6: Canopy height map derived from discrete LiDAR (5 pl m^{-2}) for Mulligans Flat Nature Reserve, ACT (a). Correlation between field and discrete LiDAR derived tree height for 28 trees at Mulligan's Flat Nature reserve (b). This LiDAR data was acquired on December 2013. Source [1]

Canopy base height is a variable that can be retrieved from multiple discrete return LiDAR data. Canopy base height can be overestimated if the effect of the extinction of the laser signal through the canopy is not accounted for in the computation of the values (Figure 7). If large shrubs are present the LiDAR derived canopy base height can be underestimated because some of the returns from the shrubs are assigned as canopy returns as they exceed the height threshold used for point classification (Figure 7). To overcome this problem it is necessary to provide a better classification of the point cloud that can distinguish between over- and understorey using more a sophisticated approach than simply using the height of the points. Alternatively, full-waveform systems permit extraction of additional points within the crowns which improves individual tree crown assessment [11].

a)



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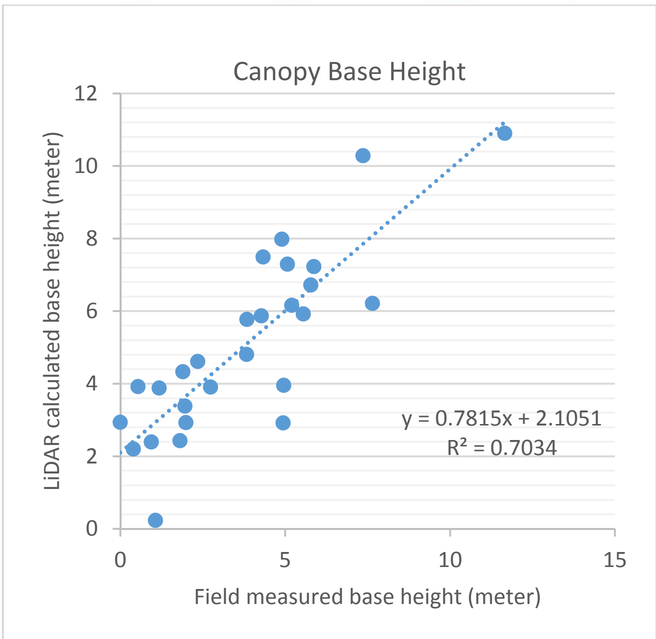

Figure 7: Canopy base height map derived from discrete LiDAR for the Black Mountain Natural Reserve (ACT) (a). Correlation between field and LiDAR derived tree base height for 28 trees at Mulligan's Flat Nature reserve (ACT) (b). This LiDAR data was acquired on December 2013. Source [1]

Canopy bulk density is described as the foliage biomass divided by the crown volume. Large tree branch biomass is not included since it has less influence on fire behaviour. However, the laser beams target all material in the canopy, thus CBD cannot be directly derived from the cloud point returned by the tree crowns. Canopy bulk density can be either empirically estimated from LiDAR metrics (for example, canopy height) and field measurements using so-called allometric equations, or from the foliage biomass and crown volume. Allometric equations have also been used to predict crown and foliage biomass [12], providing accurate canopy bulk density estimations at plot level. The same study also used LiDAR to directly provide a direct crown volume estimate, producing better results than directly fitting any of the LiDAR variables to CBD.

Canopy continuity or **cover fraction** is inversely related to the laser pulse penetration rate into the canopy. Canopy continuity has been successfully estimated from airborne LiDAR as the proportion of the canopy returns over all the returns (Figure 8). The accuracy of LiDAR-derived canopy cover fraction is very good and comparable to, or even better than, field-based estimates [13-15] .

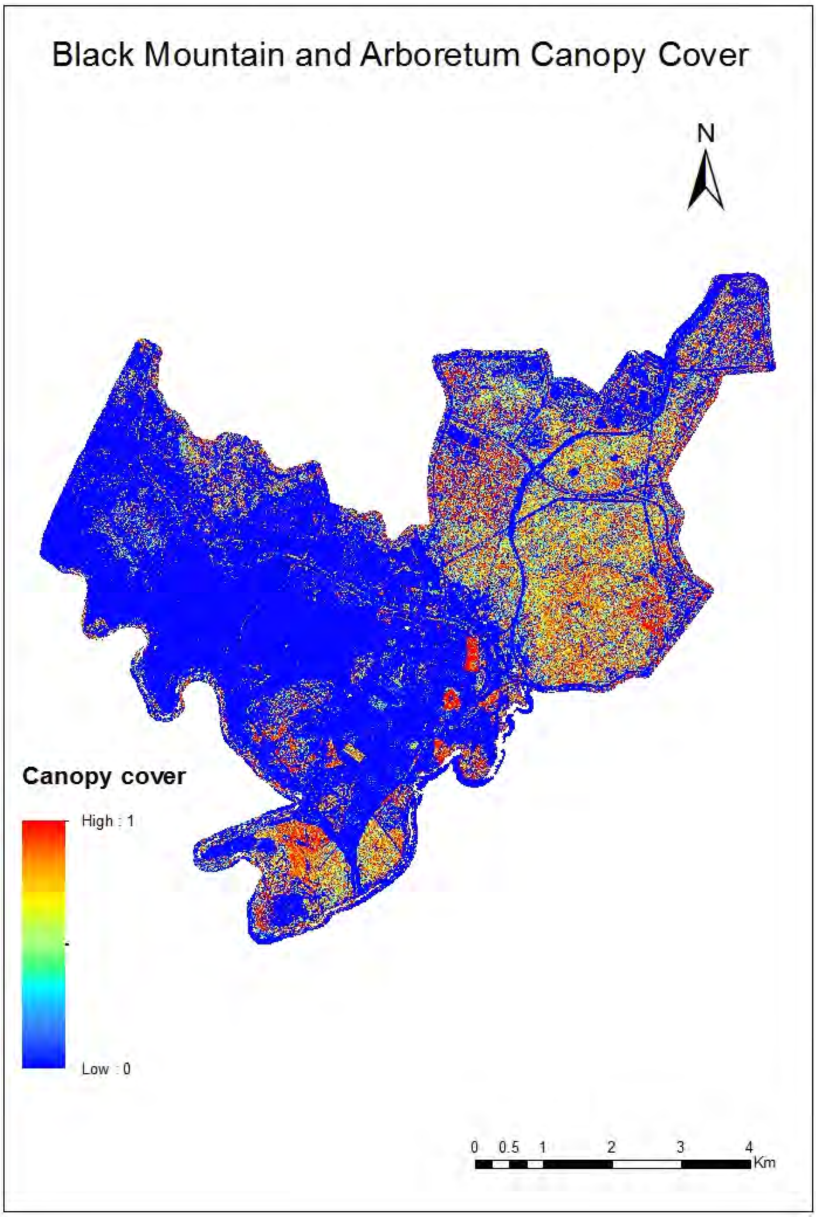

Figure 8. Map of Black Mountain Nature Reserve showing the fractional cover of the canopy using LiDAR acquired on December 2013. Source, [16] http://www.bnhcrc.com.au/resources/poster/1233.

Understorey

The ability to map understorey vegetation structure is important as the lower vegetation acts as a fuel ladder for crown fires (Figure 9). However, LiDAR does have limitations in obtaining data about the understorey. Point density and footprint size impact the understorey fuel measurements as well as the spatial resolution. These are important considerations when deciding on whether to collect LiDAR or whether existing LiDAR data is suitable: point density, footprint size and spatial resolution can all be improved, but this comes at greater cost of acquisition (see Section 6).

Furthermore, higher point density is not always sufficient in very dense forests: some studies using a high point density (10 pl m^{-2}) still had difficulties in detecting young regeneration in the understorey ([17]). Similarly, a study that used high point density (9 pl m^{-2}) small-footprint LiDAR data along with multispectral imagery to predict surface fuel models and fuel metrics in a mountainous forest had limited success [18]. Shrub metrics were measured with reasonable accuracy (correlation coefficient greater than 0.5), but ground-based fuels less so (coefficient below 0.5). It should be noted that these forests were considerably denser than most Australian forests at risk of fire.

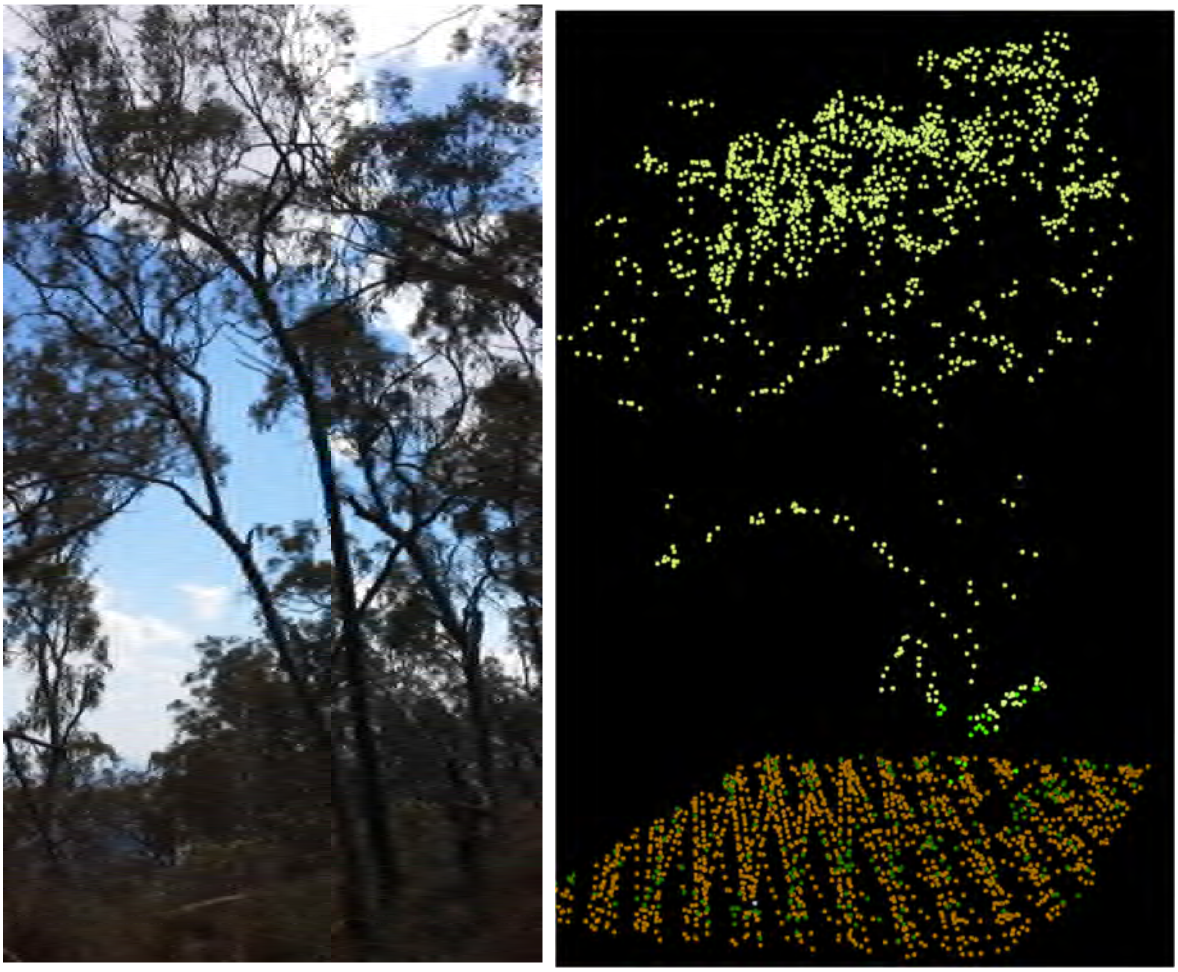

Figure 9. The photo on the left shows a relatively open stand with ladder fuels and the photo on the right the way multiple discrete return LiDAR represents this stand.

Full-waveform LiDAR is superior and preferable to discrete pulse data in dense forests as the waveform contains larger number of smaller peaks in return intensity than the amount extracted forming a discrete return dataset, which allows small understorey trees to be detected, with higher the point density resulting in better information. Some researchers, however, have found that a point density beyond 10 pl m^{-2} does not improve the detection rate much however [19]. Full-waveform LiDAR has also been proven more successful when there is tall grass or steep slopes.

Below, a summary is provided of the ability to derive information on understorey fuel attributes using airborne LiDAR.

Understorey height, which can relate to elevated fuel height or near-surface fuel height, depending on height overall, is difficult to obtain from a large footprint LiDAR sensors but small footprint LiDAR sensors have provided reasonable results [20]. Figure 10 shows a discrete LiDAR -derived understorey height map for the Black Mountain Reserve in the Australian Capital Territory (ACT). In this case, a limitation of the map is that the maximum height of the understorey depends on the classification of the point cloud, which is typically provided by the commercial data provider based on standard definitions. When points representing shrubs are higher than a specific threshold they are classified as canopy returns while in reality these returns relate to the understorey. This leads to an underestimation of the understorey vegetation height that can be resolved by using a better classification of the point cloud.

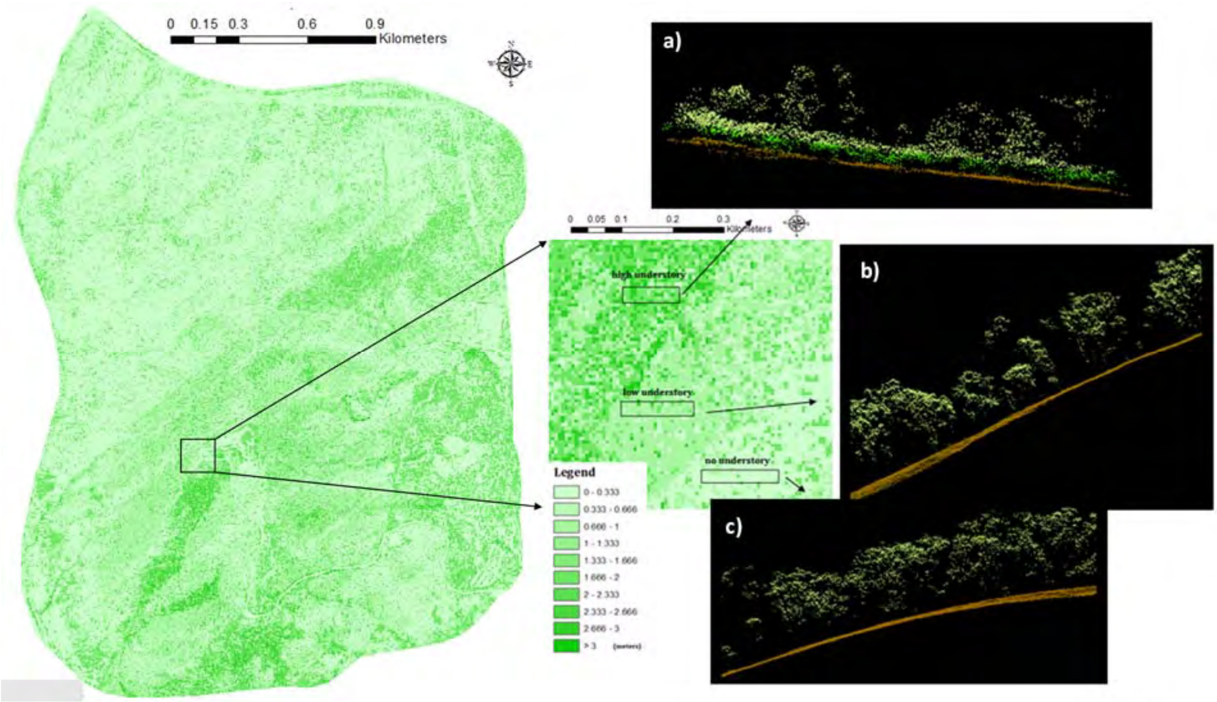

Figure 10. Discrete LiDAR-derived understorey height for the Black Mountain Reserve. Transect "a" shows that when the values are higher the understorey is higher. When the values are low the understorey is either absent (transect "c") or almost absent (transect "b") Source [1]

Understorey cover fraction can be estimated from LiDAR by dividing the number of below-canopy vegetation returns by the sum of below-canopy and ground returns. The error in the understorey cover estimation decreases with LiDAR pulse density. For example, [17] conclude that understorey cover mapping requires more than 1 pl m^{-2} returns at minimum. Figure 11 is a map of understorey cover derived from LiDAR data with a density of 5pl m^{-2} on Black Mountain, ACT. Similarly to understorey height, there are inaccuracies in the points that are classified as understorey returns, and there is some evidence that the signal is extinguished in the lower canopy [1]. New methods to accurately obtain understorey vegetation cover information at fine spatial resolution are in development. For example, the understorey LiDAR points can be filtered by return intensity values. When measured in correlation coefficient (r^2 in %, where 100% indicates perfect mapping), this was shown to increase the accuracy to 70–80% compared to 20–45% for methods without using the return intensity [21].

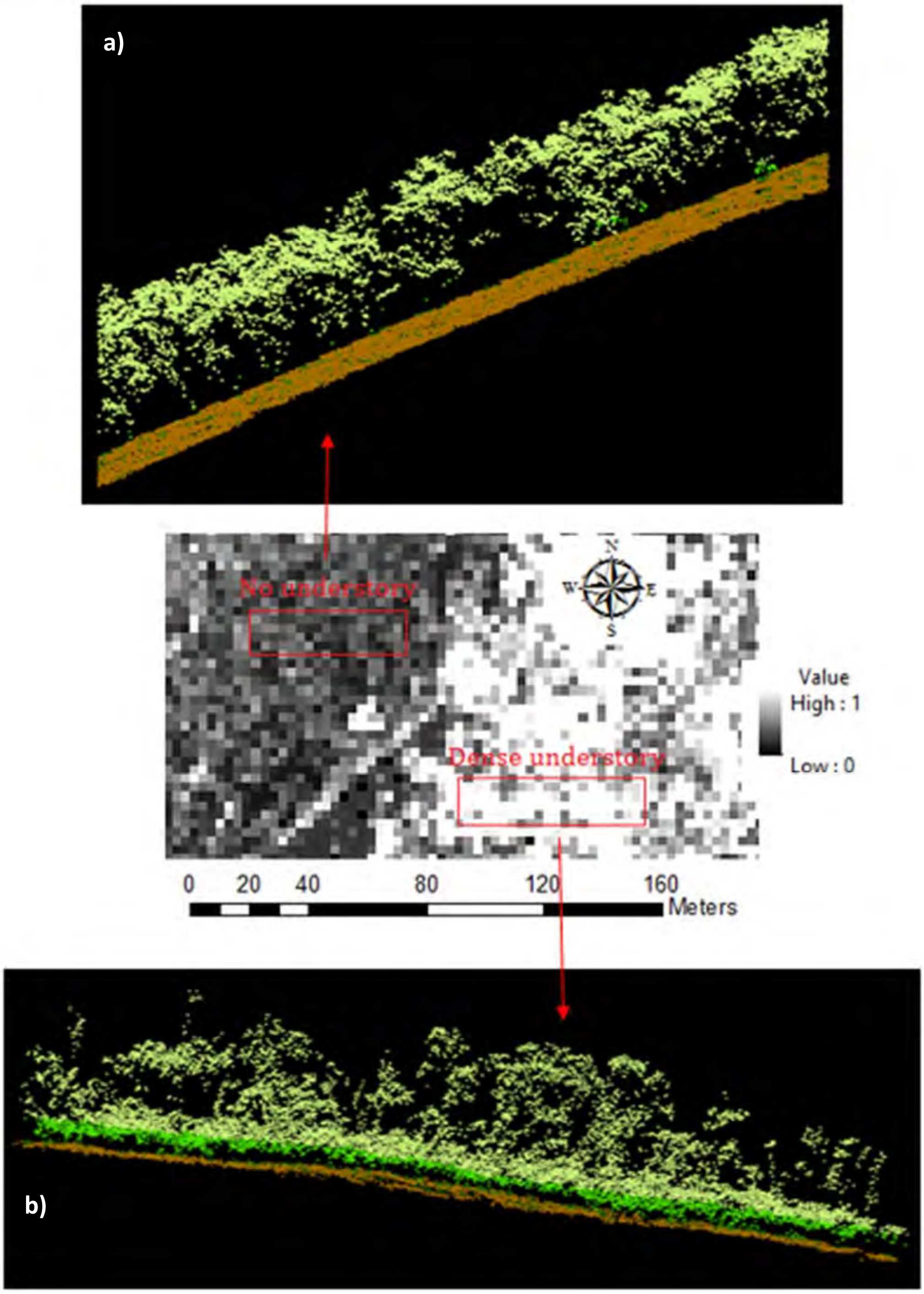

Figure 11. Examples of fractional cover of the understorey with some side views of transect belonging to areas with a) relatively low cover values and b) high values for understorey cover. The side views show that there is little understorey when the fractional cover value is low and that there is a lot of understorey when the values are high. Source [1].

Near surface fuel is very important in fire hazard and fire behaviour estimations as it can re-accumulate quickly after fire, can dry quickly due to increased exposure, and is a critical variable in determining fire behaviour [7]. Unfortunately, LiDAR data can have difficulties in detecting this fuel category, depending on how much vegetation is overhead. Misclassification between the solid ground and low vegetation can also be a problem [22]. The pulse intensity derived from multiple return LiDAR may be used to avoid such misclassifications as shown in Figure 12. However roughness of the solid ground (such as stones and coarse debris), slope, and vegetation litter can prevent high accuracy in classification. In such cases, full-waveform LiDAR can be useful to differentiate low vegetation from the ground.

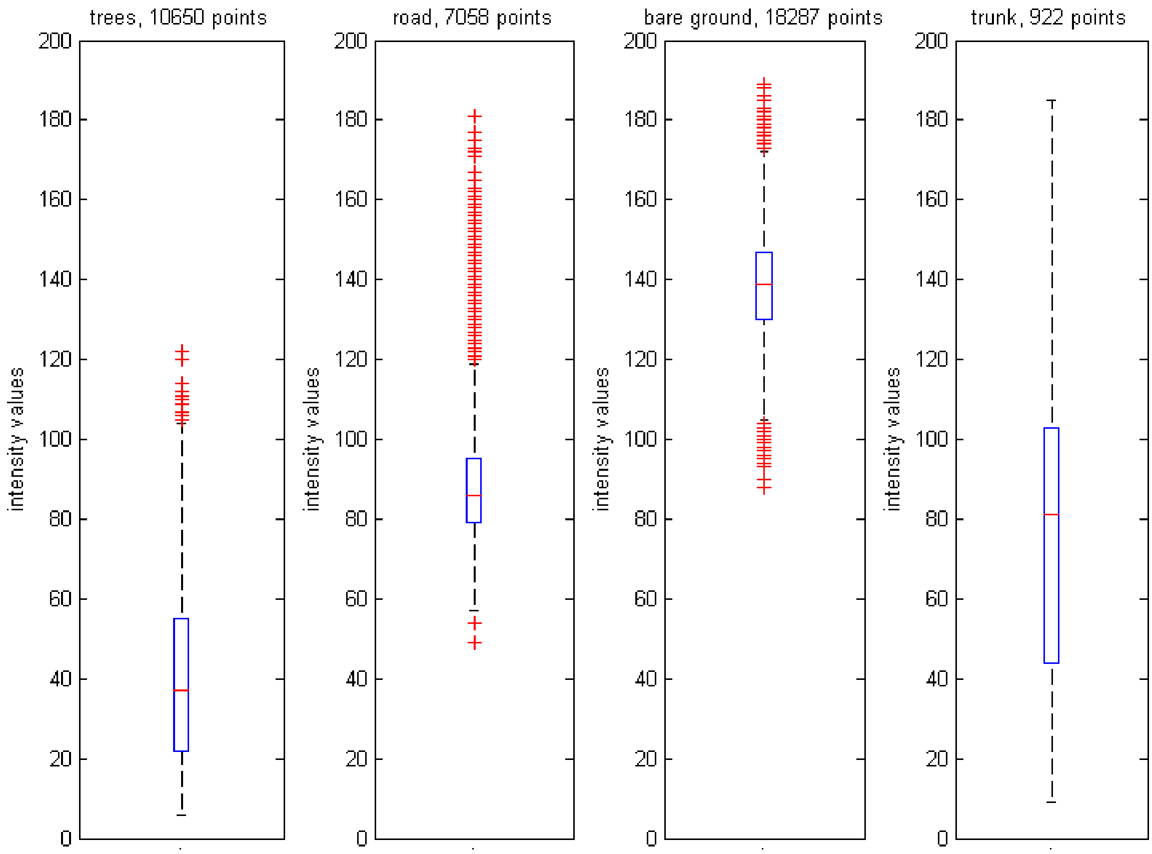

Figure 12. Boxplots showing the distribution of the intensity values over four classes of materials: trees, road, bare ground and trunk. A difference in intensity values is apparent between the different materials (Source [1])

Other uses in fire management

In addition to fuel parameters and attributes, LiDAR can also be used to provide other valuable information for fire management. In particular, knowing the solid ground surface accurately can help greatly in the fire management operations and emergency response. For example, detailed knowledge of creeks, rock shelves and existing roads, fire trails and old tracks can assist in planning control lines for hazard reduction burning and firefighting exercises [23].

4. Measurements that help maximise the value of airborne LiDAR

Much information about the forest canopy can be reliably derived from airborne LiDAR data. However, conventional multiple return airborne LiDAR may not always provide the amount of detailed information on understorey that is needed in fire assessments and fire behaviour models. Full-waveform LiDAR has the potential to provide the desired detail, but this currently comes at considerably greater costs in data acquisition and processing. Other approaches to maximise the value of airborne LiDAR remote sensing are discussed below.

Terrestrial LiDAR scanning

Terrestrial based LiDAR (TLS) provides extremely detailed data on under- and mid-storey vegetation. For example, the ECHIDNA® LiDAR data system, developed by CSIRO and Boston University, has been used various times to assess forest structural parameters [24] [25]. Such studies emphasise that TLS data provide enormously detailed and accurate data about the stems of the trees and diameter at breast height, for example. The new dual wavelength echidna LiDAR (DWEL, Figure 13) contains two lasers of different wavelength, allowing it to distinguish between green leaves and the woody vegetation within a single scan. The main disadvantage of systems such as the ECHIDNA and DWEL is that they are not hand-held. They are mounted on a tripod and have to be stable while collecting data. Therefore they can only collect LiDAR data for a limited area surrounding the system, and mapping large areas is very problematic with efficiency and transport overheads making this a very cumbersome process.

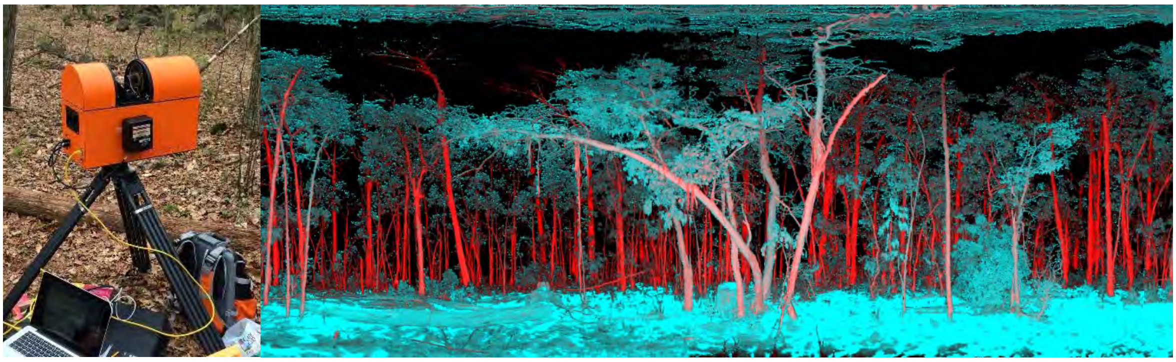

Figure 13. New DWEL laser scanner (left) and a normalized normalised difference index (NDI) image of the woodlands of Mulligans Flat Natural reserve produced by the DWEL (right). NDI was computed using the laser reflectance at 1064nm and 1556nm. The NDI image easily define the trunks and the leaves. Very "green" vegetation should appear blue, Red sections of the image relate to non-green vegetation components. Courtesy of Michael Schaefer.

Hand-held LiDAR systems such as CSIRO's Zebedee provide more flexibility for rapidly collecting LiDAR data on the ground [26] (Figure 14). The Zebedee instrument provides detailed information of the lower part of the forest and opens enormous opportunities for fuel research and monitoring. Initial research through the Bushfire and Natural Hazards CRC has shown great promise in mapping the presence and density of different fuel layers within an area of interest (Figure 15).

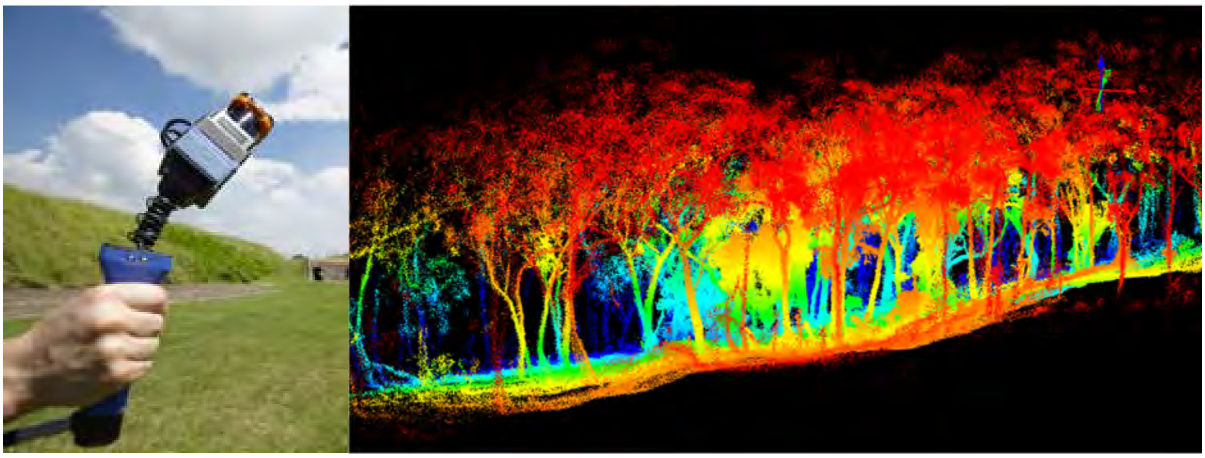

Figure 14. Zebedee (left, source, http://www.csiro.au/Organisation-Structure/Divisions/Computational-Informatics/Zebedee-3D-mapping.aspx). Ground based Zebedee-LiDAR data collected at Black Mountain reserve, Australian Capital Territory (right, Source, [16] http://www.bnhcrc.com.au/resources/poster/1233).

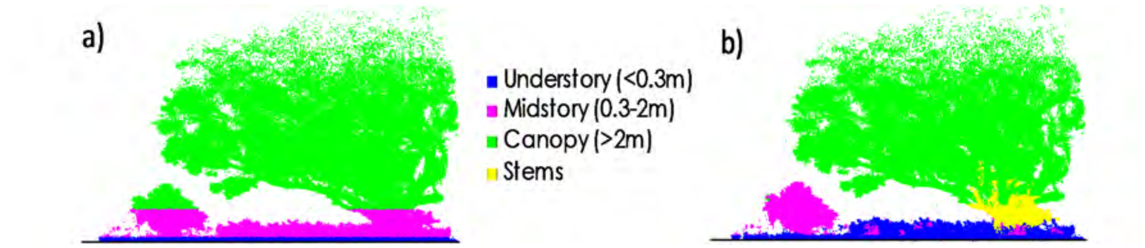

Figure 15. Fuel classification with Zebedee a) Based on the presence of points classified within a specific height layer b) using an algorithm that re-classifies the previous output based on forest fuels rules. The later better distinguishes between forest fuel layers with some minor noise. Source, [16] http://www.bnhcrc.com.au/resources/poster/1233.

TLS may be preferred over airborne LiDAR in some situations. It is more cost-effective over small areas and requires less time for planning, yet yields highly accurate information of the understorey. These advantages make TLS particularly useful in applications requiring repeat surveys or monitoring with a high temporal resolution, particularly when highly accurate or detailed vegetation structure data are needed. Aerial surveys provide a more complete view of the tops of canopies and a more spatially comprehensive view of a larger area [27]. TLS data can also be merged with airborne LiDAR, filling in the gaps of information present in the LiDAR data and providing a more accurate and complete 3D view of fuel (Figure 16)

Hand-held systems such as the Zebedee allow for larger areas to be surveyed than stationary TLS systems. Time, accessibility and processing costs still limit the extent to hectares rather than square kilometres, however. Instruments such as the Zebedee may offer an attractive solution to map fuel structure at different times before and after a planned burn, to rigorously determine the change in fuel availability that has resulted in a way that is highly consistent and reproducible.

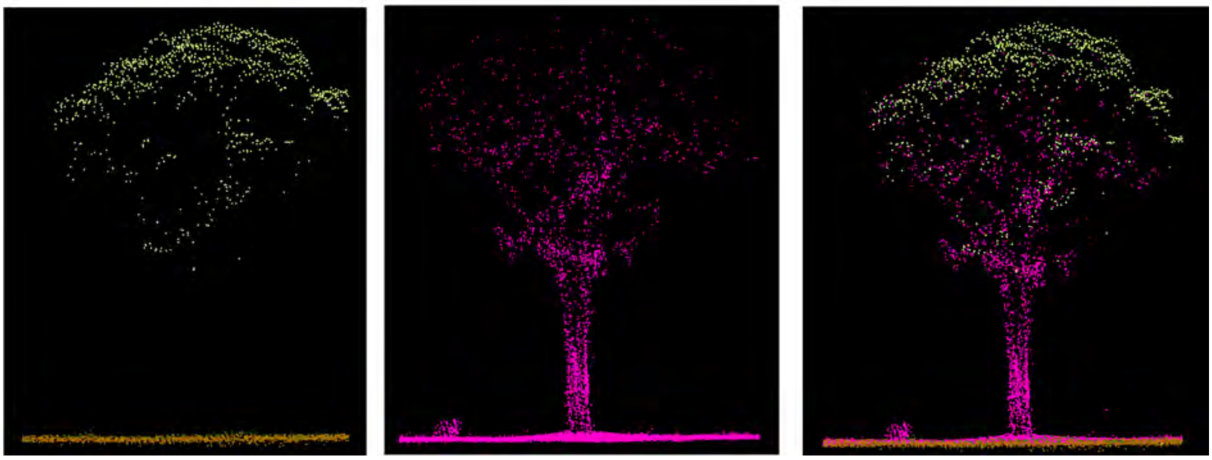

Figure 16. Airborne and ground-based LiDAR dataset complement each other very well since airborne LiDAR captures the canopy whereas ground-based LiDAR accurately measures the ground and elevated fuels. Source, [16] http://www.bnhcrc.com.au/resources/poster/1233.

Unmanned Aerial Vehicle mounted LiDAR systems

Unmanned Aerial Vehicle (UAV)-mounted LiDAR systems are rapidly developing. UAV-LiDAR systems provide an unrivalled combination of high temporal and spatial resolution datasets, with densities up to 150 points per square meter (Figure 17). These very high resolution point clouds allow measurements of tree height, location, and canopy width to be made with errors as small as 0.05 m for height, 0.44 m for location and 0.25 m for canopy width [28]. It should be noted, however, that when mapping understorey characteristics UAV-LiDAR data fundamentally still has the same drawbacks as other airborne data, albeit that the much higher point density can help to reduce mapping error and increase the amount of information from lower vegetation layers.
UAV systems can be owned and deployed by fire management agencies themselves, which potentially increases their value in operational fire management. However, regulations from the Civil Aviation Safety Authority (CASA) may impose serious restrictions on what it can be done with UAV Lidar systems.

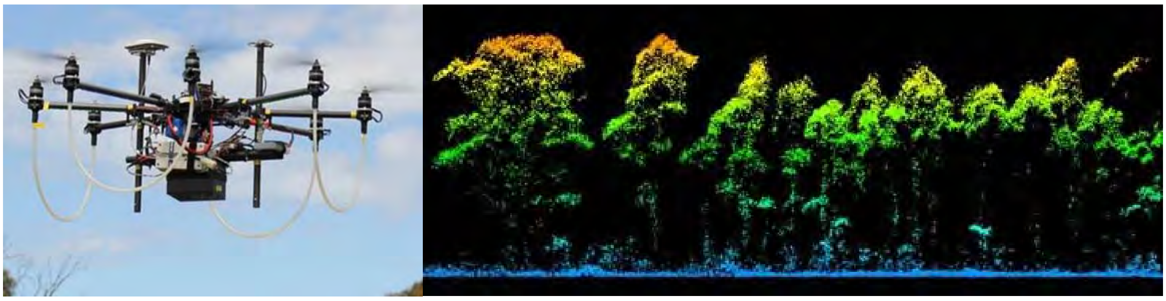

Figure 17. The multi-rotor Oktocopter UAV platform carrying the laser scanner (left), An example point cloud at an average point density of 40 points per square meter (right). Source [28].

Photographic and hyper-spectral data

Airborne or ground-based LiDAR can be used to obtain highly accurate data on the full 3D structure of the vegetation. However it provides little information to help distinguish different fuel types (for example, wood, bark, leaves and litter) and does not provide information on the water content of the fuel. This can be achieved by combining LiDAR data with other airborne or satellite remote sensing data.

For example, Project VESTA fuel assessments (surface fuel hazard score, near surface fuel hazard score, near surface fuel height and bark fuel hazard scores) can potentially be achieved using a combination of LiDAR and hyperspectral data (Figure 18). While LiDAR data can be used to assess the structural characteristics of the plot, the hyperspectral data can be used to assess the characteristics of the moisture and the tissue composition. Research has shown that airborne hyperspectral and LiDAR data can also be combined to predict the Victorian Overall Fuel Hazard, particularly when distinctions are made between different vegetation types [29].

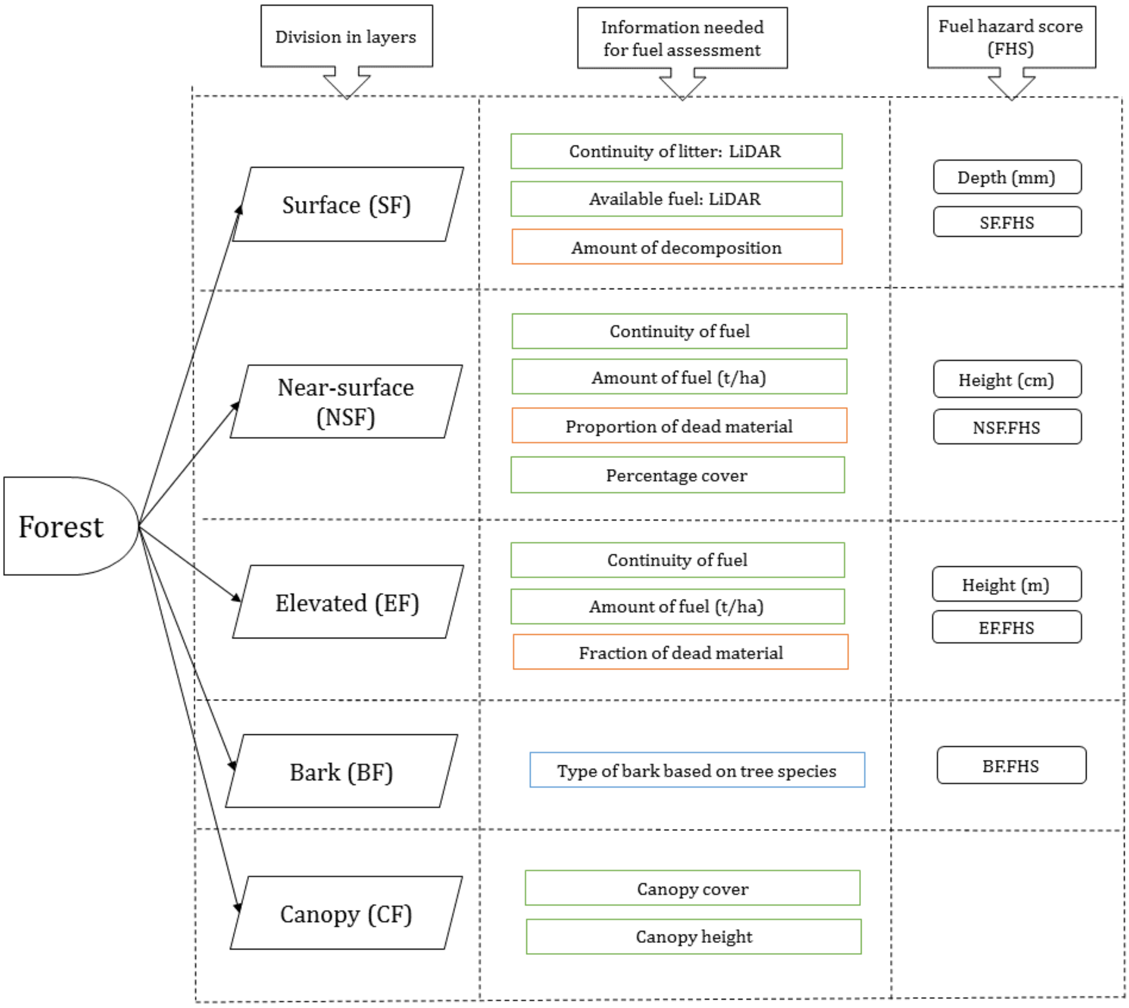

Figure 18: Theoretical framework on how to derive the variables needed for a fuel assessment from LiDAR (green) and hyperspectral (orange) data. Structural parameters on the different vegetation layers can be derived from airborne and terrestrial LiDAR data. Complementary hyperspectral data can be used to derive fuel moisture, amount of decomposition, proportion of dead material and even type of bark though specise classification. Source, modified from [1].

5. Where to find airborne LiDAR data

A recent overview of airborne LiDAR applications on forest agencies within six states of Australia showed that the only states that have not yet utilised LiDAR data for forestry purposes were the Australian Capital Territory (ACT) and the Northern Territory (NT) [30]. This situation has already changed however: the ACT collected LiDAR and hyperspectral data in December 2013 and will do so again in early 2015. Thus, the availability of LiDAR data is rapidly increasing.

As a first step, users interested in obtaining LiDAR data are encouraged to investigate what is already available. Unfortunately, LiDAR capture for the different states and territories is carried out at various levels of precision and there is not a single data set or catalogue that can be accessed. Efforts are underway to change this however.

Geoscience Australia has created a data portal (http://nedf.ga.gov.au) to host LiDAR datasets and derived products. Currently these datasets are already available for much of the Australian coastline, although so far only accessible to Government users. A collaborative effort between the Department of Communications, National ICT Australia (NICTA) and Geoscience Australia, the National Map project combines a visual map of Australia with the data sets released by the government under the open data policy, including data from the Australian Bureau of Statistics, Bureau of Meteorology, and data.gov.au. One of the National Map project's ten themes focuses on satellite data and therefore it can be expected to host LiDAR data in future, where license restrictions for data use are not a limiting factor.

Where LiDAR data are not already available, the only option is to collect them anew. Most state governments have procedures, or are developing procedures, aimed at coordinating the collection of LiDAR data so that the collected data may be more widely useful for other purposes and so that costs can be shared.

6. Cost of collecting LiDAR data

An important consideration before acquiring LiDAR data is to undertake a cost-benefit analysis on the possible different configurations and specifications that may be offered. The cost of airborne data collection usually have a fixed component (for example, a so-called mobilisation cost) and a cost per unit area.

To give an indication of pricing: at the time of this report (November 2014), the cost of acquiring aerial LiDAR for a survey area of ca. 7,000 ha is about $5.1 and $3.5 per ha for 5 and 2 pl m^{-2} laser pulse densities, respectively. The cost of providing full-waveform LiDAR data for the same area is around $7.6 per ha (Table 2). The higher cost of full-waveform LiDAR may be justified by the increase in detail and accuracy in understorey information. Overall, for comparison, the cost of LiDAR is higher when compared to the cost of acquiring digital aerial imagery for the same area, which lies at around $1 per ha (with similar mobilization costs).

Table 2. Comparative cost of different LiDAR systems and acquisition characteristics.

LiDAR type	Point density	Vertical accuracy	Horizontal accuracy	AU$ ha^{-1}
Discrete	2	0.20 m	0.30 m	3.5
Discrete	5	0.20 m	0.30 m	5.1
Full wave	8	0.07 m	0.14 m	7.6

TLS instruments are available at costs between $23k (Zebedee) and $250k (DWEL), while the latest AUV-LiDAR system released costs $500k. This is only the cost of the initial instrument purchase, of course there will be additional cost for training, field operation, data management, instrument maintenance, and others. By comparison, the main costs associated with manual on-ground methods include travel, field data collection and data entry.

The long-term trend in any airborne data collection is that prices will reduce in future years. The evolution of LiDAR technology will continue to enhance data quality and richness. Pulse repetition rates and flying heights will continue to increase, allowing for denser and more cost-effective surveys.

Anyone considering to purchase LiDAR data is strongly recommended to contact LiDAR contractors for accurate, up to date pricing for alternative acquisition characteristics.

7. Processing LiDAR data

End users may be able to process LiDAR data by themselves or may need to outsource it, depending on purposes, the capacity to use LiDAR-related geospatial software and programming languages, and access to such software.

Processing LiDAR data requires knowledge of LiDAR techniques, familiarity of geospatial software, and programming skills. It also requires the accessibility to the processing software. A single program may not be able to achieve various purposes or relatively complex spatial analysis. Geospatial programs are often used together with programming languages such as Matlab or Python for more sophisticated LiDAR data analysis.

Some technically detailed guidance on data format and software is provided below and summarised in Table 3. As a first approach, users may consider approaching technical staff responsible for spatial data management in their organisation and ask them to consider these details and assess the capacity to undertake such analysis. If such a specialist is not available in the organisation, outsourcing may be a more attractive option.

LiDAR generates a large amount of point cloud data in three dimensions. Originally, LiDAR data was only delivered in ASCII format. However, the reading and interoperation of ASCII files requires a lot of processing time, due to extremely large size of files, even for small amounts of data. In order to overcome this problem, Log ASCII Standard (LAS) files were adopted to manage and standardise the way in which discrete return LiDAR data was organized and disseminated. A LAS file is an industry-standard binary format created and maintained by the American Society for Photogrammetry and Remote Sensing (ASPRS), and also is a published standard file format for the interchange of LiDAR data.

Various software products are available to read, display, process, and analyse LAS files, such as PointVue, Quick terrain reader, Quick terrain modeler, GeoCue LAS Reader, LAS Convention Tools (LAStools and LASUtility), ENVI LiDAR, ERDAS IMAGINE 2014, and ESRI ArcGIS for Desktop products (ArcScene). The end users may want to consider different software solutions according to their accessibility in terms of license, cost, performance, and processing time, as well as the familiarity of programs.

To visualize three-dimensional LiDAR point cloud data in LAS files, PointVue, Quick terrain reader, ENVI LiDAR, ERDAS IMAGINE 2014, or ArcScene are recommended. If end users are familiar with command line based software, LAStools can be used to read and write LAS files. LASUtility is similar to LAStools, and also offers the ability to view LAS headers, convert LAS format to ASCII format and merge or subset LAS files. LASUtility is a Java application that includes a graphical user interface to the commands.

ERDAS IMAGINE 2014 provides a suite of new operators added to the 2014 Spatial Modeller to assist in the creation of custom workflows that include LiDAR LAS files. ENVI LiDAR can also be used to create LiDAR data visualizations and easily extract three dimensional features. With the ENVI LiDAR API, users can customize the application to meet the various needs, such as, adding algorithms and custom tools and creating batch processes. It is also used in conjunction with other geospatial software tools, like ESIR ArcGIS, in order to perform additional spatial analysis.

ESRI ArcGIS for Desktop is recommended if the end users have access and are familiar with Python. It supports LiDAR data provided in either ASCII or LAS file format. LAS attributes (for example, x, y, z, intensity, class codes, and TGB colour values) can be used to symbolize points in two and three dimensions. ArcGIS also provides the ability to define logical sets of LAS files for working in localized projects. GeoCue LAS Reader is a plug-in LiDAR exploitation solution for the ArcGIS desktop products. ArcGIS can be used to directly display and process LiDAR data, when GeoCue LAS Reader is installed. Using ArcGIS, users can quickly view LiDAR data in two and three dimensions, import LAS files into multipoint features (for example, multipoint features, rasters, and terrain datasets), update LiDAR class codes, analyse LiDAR data as a surface, process LiDAR data for various research purposes, add custom tools, and create Python Toolboxes for customised LiDAR data analysis.

Robust and dedicated software for full-waveform LiDAR processing is limited to a few proprietary products, although it is expected that future research will result in the development of dedicated open-source tools [6]. For example, Pulsewaves is an open, vendor-neutral, stand-alone, LAS-compatible full-waveform LiDAR standard software that allows to process full-waveform LiDAR (https://github.com/PulseWaves). However, it is still in development phase and does not have many processing options yet. Therefore, users seeking to use full-waveform LiDAR may wish to engage individuals undertaking active research and development in this area.

Table 3. Summary of the software products that are available to read, display, process, and analyse LAS files.

Software	Cost (AUD)	Utility	Link
Quick terrain reader	Free	3D LiDAR point cloud visualization	http://appliedimagery.com/download
Quick terrain modeller Version 8	Educational Node Lock License: 567 Academic Node Lock License: 567 Government Node Lock License: 4480	3D point cloud and terrain visualization software package	http://appliedimagery.com/download
PointVue LE	Free	3D LiDAR point cloud visualization	http://www.geocue.com/
GeoCue LAS Reader	Free	A plug-in LiDAR exploitation solution for the ArcGIS desktop products	http://www.geocue.com/
LAStools - OPEN source (LGPL 2.1)	Free	Creating DEMs from LAS data Creating TINs from LAS data Calculating convex or concave hulls from LAS data Generating contours from LAS data Advanced LAS command-line attribute processing (las2las) Plucking out first/last returns (las2las: Advanced LAS filtering and manipulation or yourself with a programatic API) Decimating data Converting data between formats (1.0 <-> 1.2, etc)	http://www.cs.unc.edu/~isenburg/lastools/
LAStools - CLOSED source	Commercial and government production license (single-seat): Individual LAStools: 1431-2862 Entire LAStools suite: 5724, BLAST extension pack: 2862 All together: 7155	LiDAR data processing tools which can also be run via a native GUI and are available as a LiDAR processing toolboxes for ArcGIS versions 9.3, 10.0, 10.1, or 10.2 and for QGIS versions 1.8, 2.0, 2.2, or 2.4.	http://www.cs.unc.edu/~isenburg/lastools/

LAS Utility	Free	Manipulating LAS files directly in C, C++, Python, .NET, and Ruby (caveats apply) Embedding LAS read/write support in your own commercial software Plucking out first/last returns (las2las: Advanced LAS filtering and manipulation or do it yourself with libLAS' programatic API) Reclassifying point data with your own algorithm(s) Decimating data Converting data between formats (1.0 <-> 1.2, etc) Converting data to OGR-writeable formats Adding coordinate system info to an LAS file Reprojecting data from one coordinate system to another Spatially indexing data for fast bounds lookup	http://www.liblas.org/download.html
ENVI LiDAR	ENVI LiDAR Windows: 1141 ENVI LiDAR Mini-Lab: 5735 ENVI LiDAR Lab: 8029 ENVI LiDAR Department: 11470	Creating LiDAR data 3D visualizations, extracting three dimensional features With the ENVI LiDAR API, users can customize the application to meet the various needs: adding algorithms and custom tools and creating batch processes Conjunct with other geospatial software tools, like ESIR ArcGIS, in order to perform additional spatial analysis	https://www.exelisvis.com/ProductsServices/ENVIProducts/ENVILiDAR.aspx
ERDAS IMAGINE 2014	IMAGINE Professional: 4543 Maintenance (12 Months): 830	Customised LiDAR data processing	http://download.intergraph.com/

ESRI ArcGIS for Desktop	Advanced Concurrent Use License: 8367 Standard Concurrent Use License: 6553 Basic Concurrent Use License: 3277	Visualising LiDAR data in two and three dimensions Providing immediate access to LiDAR data without the need for data conversion or import Supporting LiDAR data that in either ASCII or LAS file format Importing LAS files into multipoint features (for example, multipoint features, rasters, and terrain datasets) Filtering out content and symbolize points in two and three dimensions corresponding to LAS attributes (for example, x, y, z, intensity, class codes, and TGB colour values) Providing the ability to define logical sets of LAS files for working in localized projects Directly displaying and processing LiDAR data, when GeoCue LAS Reader is installed Updating LiDAR class codes Analysing LiDAR data as a surface Processing LiDAR data for various research purposes Adding custom tools Creating Python Toolboxes for customised LiDAR data analysis	http://www.esri.com/software/arcgis/arcgis-for-desktop

8. Looking ahead

Below follows a summary of the preceding sections, with a few lines to identify the level of maturity of different LiDAR applications and identify areas where further development is needed.

Discrete return airborne LiDAR may be considered a mature data product that is commercially available using established data standards. Many organisations in Australia have been investing in capturing different types of LiDAR data and are building their capability in utilizing the data to derive fuel products that can be used to model bushfire behaviour. National and state initiatives will continue to increase the easy in discovering and accessing already collected LiDAR data. That said, there are as yet no standardized processing methods to convert the LiDAR point cloud into usable information. Furthermore, standardised methods need to be developed to extract information about the vegetation structure from the data, and to quantify the accuracy of the information.

Full-waveform airborne LiDAR provides more detailed vertical structure of the canopy and understorey essential for example for ladder fuel mapping. Methods to analyse full-waveform data are less mature however, and software packages to process the data are not easy to use. This is an area of active research and development. Users are recommended to engage experts in full-waveform LiDAR if they wish to investigate its value for fire management.

Terrestrial laser scanners have the potential to give more accurate information on both over- and understorey structure with great detail. They are important in providing the best possible reference for testing airborne LiDAR methods. Their application at larger scales require time and access and therefore are limited in similar ways as visual field assessment, though with the added benefit of being far more detailed, consistent and reproducible. As such they may be valuable in repeat surveys at hectare scale or less.

UAV-borne LiDAR has characteristics much the same as airborne LiDAR, albeit that the lower and slower flight allows mapping at greater detail over smaller areas, and increases the information available about the understorey. They can also be owned and deployed by agencies themselves, which potentially increases their value in operational fore management.

Priority areas for research and development to achieve more cost-effective and successful use of LiDAR by the fire management community include, among others:

- better use of the airborne LiDAR data that are already being collected;
- specifications for future LiDAR acquisition to serve fire management applications;
- standardised methods to process airborne LiDAR data and produce fuel attribute maps;
- methods to combine LiDAR-derived maps with other spatial data for comprehensive fire risk mapping;
- standardised methods to validate LiDAR-derived fuel attribute maps; and
- applications of new LiDAR measurement technologies, including full-waveform LiDAR, terrestrial laser scanning and UAV-borne LiDAR.

The Bushfire and Natural Hazards CRC project ‘Mapping bushfire hazard and impacts’ pursues these lines of investigation, working with end users to identify their information needs, identify current capabilities and develop standard methods and tools that will provide timely standardised fuel information at lower cost.

References

1. Marselis, S., *Mapping forest fuel structure with LiDAR data*. 2014, Australian National University.
2. Gould, J., J. Hollis, and M. Cruz, *Australian Fuel classification. Overview and Framework*, in *AFAC*. 2012: Perth.
3. Gould, J.S., W. Lachlan McCaw, and N. Phillip Cheney, *Quantifying fine fuel dynamics and structure in dry eucalypt forest (Eucalyptus marginata) in Western Australia for fire management.* Forest Ecology and Management, 2011. **262**(3): p. 531-546.
4. Hines, F., et al., *Overall fuel hazard assessment guide*. 2010, Melbourne: Department of Sustainability and Environment. .
5. Gould, J., et al., *Field Guide: Fire in Dry Eucalypt Forest: Fuel Assessment and Fire Behaviour Prediction in Dry Eucalypt Forest*. 2008: CSIRO PUBLISHING.
6. Gould, J., M. Gomes Da Cruz, and T. Jovanovic, *Australian fuel classification: stage III. ACT pilot study*. 2012. p. 68.
7. Cheney, N.P., et al., *Predicting fire behaviour in dry eucalypt forest in southern Australia.* Forest Ecology and Management, 2012. **280**(0): p. 120-131.
8. Cruz, M.G., M.E. Alexander, and R.H. Wakimoto, *Assessing canopy fuel stratum characteristics in crown fire prone fuel types of western North America.* International Journal of Wildland Fire, 2003. **12**(1): p. 39-50.
9. Cruz, M.G., et al., *Fire behaviour modelling in semi-arid mallee-heath shrublands of southern Australia.* Environmental Modelling & Software, 2013. **40**(0): p. 21-34.
10. Zimble, D.A., et al., *Characterizing vertical forest structure using small-footprint airborne LiDAR.* Remote Sensing of Environment, 2003. **87**(2–3): p. 171-182.
11. Chauve, A., et al., *Processing Full-Waveform Lidar Data to Extract Forest Parameters and Digital Terrain Model: Validation in an Alpine Coniferous Forest.*, in *ForestSat Conference*. 2008. p. 5.
12. Riaño, D., et al., *Generation of crown bulk density for Pinus sylvestris L. from lidar.* Remote Sensing of Environment, 2004. **92**(3): p. 345-352.
13. Weltz, M.A., J.C. Ritchie, and H.D. Fox, *Comparison of laser and field measurements of vegetation height and canopy cover.* Water Resources Research, 1994. **30**(5): p. 1311-1319.
14. Hyde, P., et al., *Mapping forest structure for wildlife habitat analysis using waveform lidar: Validation of montane ecosystems.* Remote Sensing of Environment, 2005. **96**(3–4): p. 427-437.
15. Riaño, D., et al., *Modeling airborne laser scanning data for the spatial generation of critical forest parameters in fire behavior modeling.* Remote Sensing of Environment, 2003. **86**(2): p. 177-186.
16. Yebra, M., et al. *Mapping Bushfire Hazard And Impact*. in *AFAC 2014, After disaster strikes, learning form adversity.* 2014. Wellington.
17. Jakubowski, M.K., Q. Guo, and M. Kelly, *Tradeoffs between lidar pulse density and forest measurement accuracy.* Remote Sensing of Environment, 2013. **130**(0): p. 245-253.
18. Jakubowksi, M.K., et al., *Predicting surface fuel models and fuel metrics using Lidar and CIR imagery in a dense, mountainous forest.* Photogrammetric Engineering & Remote Sensing, 2013. **79**(1): p. 37-49.
19. Reitberger, J., P. Krzystek, and S. U., *Benefit of airborne full waveform LiDAR for 3D segmentation and classification of single trees.* , in *ASPRS*. 2009: Baltimore, Maryland
20. Lee, A., R. Lucas, and C. Brack, *Quantifying vertical forest stand structure using small footprint lidar to assess potential stand dynamics.* Proceedings, NATSCAN—Laser scanners for forest and landscape assessment instruments, processing methods and applications, 2004: p. 3-6.
21. Wing, B.M., et al., *Prediction of understory vegetation cover with airborne lidar in an interior ponderosa pine forest.* Remote Sensing of Environment, 2012. **124**(0): p. 730-741.

22. Riaño, D., et al., *Estimation of shrub height for fuel-type mapping combining airborne LiDAR and simultaneous color infrared ortho imaging.* International Journal of Wildland Fire, 2007. **16**(3): p. 341-348.
23. Rusell, T., *An overview of Airborne LIDAR applications in New South Wales state forests*, in *ANZIF COnference*. 2007: Coffs Harbour.
24. Strahler, A.H., et al., *Retrieval of forest structural parameters using a ground-based lidar instrument (Echidna®).* Canadian Journal of Remote Sensing, 2008. **34**(sup2): p. S426-S440.
25. Yao, T., et al., *Measuring forest structure and biomass in New England forest stands using Echidna ground-based lidar.* Remote Sensing of Environment, 2011. **115**(11): p. 2965-2974.
26. Bosse, M., R. Zlot, and P. Flick, *Zebedee: Design of a Spring-Mounted 3-D Range Sensor with Application to Mobile Mapping.* Robotics, IEEE Transactions on, 2012. **28**(5): p. 1104-1119.
27. Lim, S., et al., *Accuracy assessment of a mobile terrestrial lidar survey at Padre Island National Seashore.* International Journal of Remote Sensing, 2013. **34**(18): p. 6355-6366.
28. Wallace, L., et al., *Development of a UAV-LiDAR System with Application to Forest Inventory.* Remote Sensing, 2012. **4**(6): p. 1519-1543.
29. Roff, A.M., et al. *Hyperspectral and Lidar remote sensing of forest fuel loads in Jilliby State Conservation Area.* . in *13th Australasian Remote Sensing and Photogrammetry Conference*. 2006. Canberra.
30. Turner, R., et al. *A national overview of airborne lidar application in Australian forest agencies*. in *11th International Conference on LiDAR Applications for Assessing Forest Ecosystems*. 2011. University of Tasmania, Australia, .