

## Detecting Change in Burnt Landscapes using a Terrestrial LiDAR System

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### Abstract

A Terrestrial LiDAR system or Terrestrial Laser Scanner (TLS) was used to detect changes in burnt landscapes. Since wildfires are a common occurrence in the Australian landscape, prescribed burns are routinely carried out by land management agencies and government departments. These prescribed burns reduce the fuel load which decreases the severity of subsequent unplanned wildfires.

Recent advances in LiDAR have enabled the successful measurement of complex structures in the field with both high accuracy and precision. LiDAR remote sensing has been used for estimating a wide variety of forest metrics. However, airborne LiDAR in particular has been unsuited for measuring understorey vegetation. Modern ground-based LiDAR systems can overcome some of the shortcomings of airborne LiDAR systems (sub-centimetre resolution, canopy obscuration).

In this study, four plots of 10m radius were chosen within a prescribed burn area in St. Andrews, Victoria which took place in April 2012. One plot was unburnt (control) while the other three plots were given different fire treatments to simulate different fire severities. The TLS was operated from the centre of the plot and data was collected at a resolution of 10mm at a radius of 10m. Laser scans were captured pre-burn, and post-burn in week two. Data analysis was carried out at different scales (voxel and plot) and at the vertical strata comprising near-surface and surface fuel layer within 1m from the ground. Within voxels, metrics used to compute change were changes in point density and maximum z value. At the plot scale, change in volume was computed. Preliminary results demonstrate the potential of TLS to detect changes at both fine and coarse scales. Metrics such as point density are misleading because of issues around occlusion. At the plot scale, changes in volume are a good indicator of fuel consumption at the near-surface and surface fuel layer and appear to be in agreement with the different fire treatments which were given to the plots.

The benefit of using a TLS is the potential for quantifying the amount of fuel consumed by a prescribed burn. TLS data can provide a quantifiable measure of post-fire effects in the understorey strata and structure of a forest. This is in contrast to current practices which rely largely on visual assessments which have some level of subjectivity and lack repeatability.

*Key words:* Terrestrial LiDAR, fire effects, burn severity, prescribed burns, fuel hazard

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## Introduction

Fires occur over the majority of the Australian landscape and in most vegetation types, making it one of the most fire-prone continents and countries on Earth (Gill, 1975). Over the past decade, a surge in the incidence and frequency of large, uncontrolled fires has occurred on all vegetated continents (Bowman et al., 2009, Golson, 1972) causing environmental damage, human suffering and economic loss (Davies et al., 2008, Lentile et al., 2006).

To prevent the occurrence of catastrophic unplanned wildfires in Australia, state government departments and land management agencies have resorted to prescribed burning, a practice that is defined as the deliberate application of fire to forest fuels under specified conditions to attain well-defined management goals (Fernandes and Botelho, 2003). Prescribed burning ensures protection of forests, wildland resources and infrastructures at urban interface, thereby ensuring human safety (Fernandes and Botelho, 2003, Gill, 1999).

Due to these increases in wildfire and prescribed burning activities, significant attention is being paid to them because of the wide range of ecological, economic, social and political values at stake (Lentile et al., 2006). Traditionally, both scientists and land managers have relied on remote sensing technologies, particularly satellite remote sensing to extend their knowledge and quantify fire effects on landscape (Pereira et al., 1997, Van Wagendonk et al., 2004). Satellite data is useful for this purpose because it can be used to qualitatively and quantitatively evaluate burnt landscapes at various temporal and spatial scales, they are cost effective, cover inaccessible areas and capture data from parts of the electromagnetic spectrum (i.e. infrared, near-infrared and middle infrared) that permit investigation into the fire effects on landscape (Chen et al., 2008, Norton et al., 2009, Rogan and Yool, 2001).

Burn severity has been mapped based on spectral changes (e.g. Miller and Thode, 2007, Soverel et al., 2010), burn area (e.g. Martín et al., 2002, Silva et al., 2005) and physiological vegetation response to fire (e.g. Lentile et al., 2007, Solans Vila and Barbosa, 2009). However, the structural response of vegetation in response to fire is still largely unexplored. Indeed, Lentile et al. (2006) have pointed out the inability of 2-Dimensional (2-D) satellite imagery to infer structural parameters of vegetation which are known to influence burn severity. They have also recommended incorporating information from both two (satellite) and three-dimensional (3-D) datasets (e.g. LiDAR) to improve estimates of post-fire effects and pre-fire fuel conditions.

LiDAR technology, especially Airborne LiDAR (ALS) is being increasingly used to study various forest structural parameters for the purpose of forest inventory (e.g. Huang et al., 2008, Moskal and Zheng, 2011, Thies and Spiecker, 2004, Watt et al., 2003). However, in the last few years, research into the applicability of ground-based LiDAR or Terrestrial Laser Scanner (TLS), a relatively new technique to measure forest metrics such as canopy height (e.g. Watt et al., 2003), tree diameter (e.g. Watt and Donoghue, 2005), LAI (e.g. Jupp et al., 2009), canopy gap fraction (e.g. Danson et al., 2007) and tree modelling (e.g. Teobaldelli et al., 2007) has been demonstrated by several researchers.

Although ground-based LiDAR technology as stated above has been used to measure forest structure, its applicability to detect changes in burnt landscapes remains limited. Attempts at using Airborne LiDAR have been made in this regard. Heo et al. (2008) utilised both ALS and TLS to formulate a method of estimating forest fire loss. However, they used LiDAR to extract individual tree heights and not metrics to determine forest fire loss. Wulder et al. (2009) evaluated the utility of ALS to detect changes in vertical forest structural characteristics associated with fire. Some other recent attempts have been made to quantify forest fuel load using ground-based LiDAR which are important components of fire behaviour (Loudermilk et al., 2007, Loudermilk et al., 2009). Angelo et al. (2010) have also demonstrated the utility of discrete-return LiDAR in deriving vertical profiles in conjunction with advanced classification techniques to predict the time since fire status of the vegetation in an oak scrub ecosystem in Florida.

Another study explored the potential of ALS and multispectral imagery to map conifer mortality and burn severity (White and Dietterick, 2012). Preliminary results indicated that characterising the vertical distribution of LiDAR returns before and after the burn was useful in determining the loss of the understorey strata. Rowell and Seielstad (2012) demonstrated the utility of a terrestrial LiDAR system to characterise grass, litter and shrub fuels in burned longleaf pine forests. A variety of height metrics were extracted for each grid cell including inflection point, maximum frequency value and ratio of plants above and below the inflection point. All these studies indicate that information regarding the vertical arrangement of fuel is important in understanding structural changes in response to fire.

Structural changes obtained using LiDAR have the potential to inform land managers about the fuel load consumption due to the prescribed burn. Fire ecologists and botanists would be interested to know how the vegetation has responded structurally to the fire event.

The primary objective of this paper is to demonstrate the potential of a ground-based LiDAR system to detect structural changes in burnt landscapes especially in the near-surface (grass) and surface fuel layer (litter) at both fine (voxel) and coarse (plot) scale using metrics derived from 3-D point cloud data.

## Methods

### Study area

The study area School Road Reserve is located in St Andrews (Victoria), approximately 36km northeast of metropolitan Melbourne (figure 1). The forest type was typical of a dry sclerophyll forest with a grassy understory (figure 2). It was very open with the absence of mid-storey vegetation, with the average height of the canopy between 10-12m. The planned burn area was approximately 19ha and was carried out on 15th April 2012 to develop fuel reduced areas of sufficient width and continuity to reduce the spread of wildfire and exclude fire from the surrounding township and riparian zones.

The canopy in the study area was dominated by eucalypt tree species comprising *Eucalyptus goniocalyx* (Long-leaf box), *Eucalyptus macrorhyncha* (Red Stringybark), *Eucalyptus polyanthemos* (Red Box) and *Eucalyptus melliodora* (Yellow Box). The grasses mainly comprised *Poa sieberiana* (Grey tussock-grass).

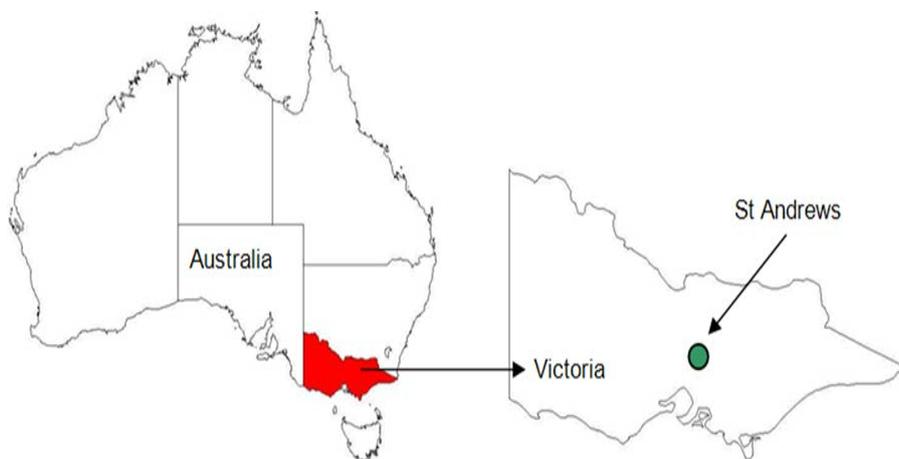


Figure 1: Location of the study area St Andrews in Victoria, Australia.



Figure 2: presentative of a typical Victorian dry sclerophyll forest with a grassy understory.

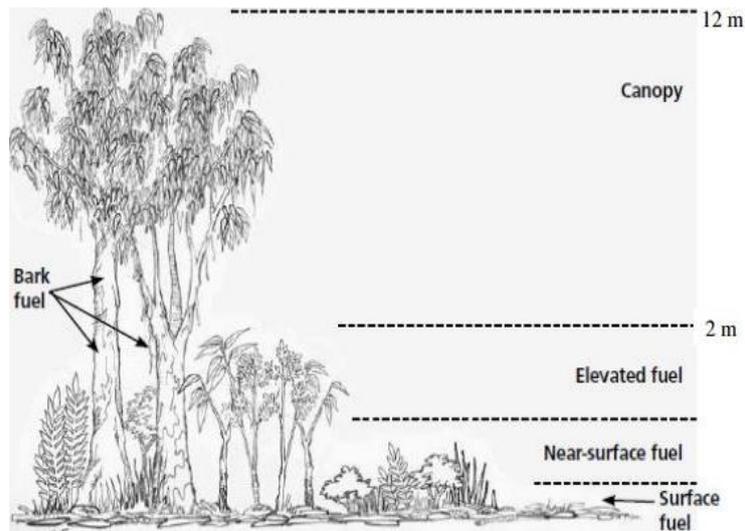


Figure 3: Vertical stratification of Victorian dry sclerophyll forests based on the vertical strata they belong to (From DSE, 2010).

The four strata of Fuels in Victorian forests comprise canopy (trees), and elevated (shrubs), near-surface (grasses) and surface (litter) fuel layers (DSE, 2010). These are shown in Figure 3.

Within the prescribed burn boundary in the study area, four circular plots of 10m radius were randomly selected. Three plots were given different fire treatments while one plot acted as a control and was left unburnt. All plots shared similar species composition and arrangement.

## Ground LiDAR

### Instrumentation

The Trimble CX ground LiDAR system uses a 660nm wavelength (red) laser with a scanning rate of up to 54,000 points per second. The maximum field of view is  $300^{\circ}$  in the vertical and  $360^{\circ}$  in the horizontal plane. It can register laser returns from as little as 0.5m away and out to a distance of 80m (at 90% target reflectivity). The Trimble CX collects: (1) x, y, z coordinate values with respect to the position of the laser sensor; (2) intensity values of the return; and (3) true colour (RGB-red, green blue) values for each point obtained from an integrated and calibrated digital camera within the instrument. The Trimble CX ground LiDAR system specifications are summarised in table 1 below.

Table 1. Manufacturer specifications of the ground LiDAR instrument (Trimble CX) used in this study

Specification Type	Specification Value
Calibrated range	80m to 90% reflective surface, 50m to 18% reflective surface
Scan rate	54,000 points per second
Output angle accuracy	$0.002^{\circ}=35\mu\text{rad}$ (horizontal and vertical)
Time of one vertical scan	20ms
Vertical scanning angle	$300^{\circ}$
Horizontal scanning angle	$360^{\circ}$
Luminance resolution	16 bits
Spot size	8mm @ 25m; 13mm @ 50m
Measuring principle	Combination of time-of-flight and phase-based measuring
Laser type	Semiconductor laser
Laser wavelength	660nm (red)
Beam divergence	0.2mrad
Weight	11.8kg
Dimensions (LxWxH)	12x52x35.5cm
Power consumption	50W
Power supply	24V DC

## Data acquisition

TLS data was acquired both pre- and two weeks post-burn in March and April 2012 respectively. The scanner was mounted on a tripod and was placed at the centre of each plot and scans were obtained in a single scan mode. The scanning resolution was set at 10mm at 10m radius. To ensure inter-comparison between scans from the same plot pre- and post-burn, the scan station was set over a known point using a video-based azimuth. Each hemispherical scan took approximately 45 minutes to complete.

## Data processing

Initially, data processing involved converting the collected laser data from binary to ASCII format. This raw data included a seven column text file containing the x, y, z coordinates, laser return intensity values and RGB values for each of the sampled return points. Data was pre-processed by first applying a vector shift to ensure no negative values existed in the x, y and z coordinates for any of the sampled return points in either of the scans. A positive shift of 1000m in x and y axes and 100m in z axis were applied for this purpose. Next, data representative of the experimental plots were clipped from the raw 3-D point cloud. Following this, voxels (three dimensional pixels) 0.5x0.5x1.0m in size were generated for further analysis. Voxels were generated by determining the minimum-z value within them. All those points within 1m from this minimum-z value were considered as being part of that particular voxel. This was done to ensure components of near-surface and surface fuel layers are adequately identified and represented for analysis as the terrain of the study area was not flat.

Structural changes beyond 1m from the ground were not looked in for in this research because no significant structural changes were observed in the canopy. The changes observed in the canopy in response to the prescribed burn event were scorching of the leaves and when the post-burn scan was acquired (2 weeks from the burn event) leaf drop had not started occurring.

The voxels within 5m from the ground-LiDAR setup were analysed separately from those more than 5m away. This was done because the decay in the ground-LiDAR signal affected the accuracy of the metrics used to measure change. Only those voxels were considered for further analysis which contained at least ten points in both the pre- and post-burn scans. Also, if in either of the scans, the number of points recorded in a voxel were zero, those voxels were also excluded from analysis. These voxels were excluded because of being highly noisy or being occluded by elements closer to the scanner. Occlusion is encountered while collecting laser scans in a single scan mode.

Different metrics were computed to understand changes in the two scans pre- and post-burn at the voxel scale, while at the plot scale only changes in volume were determined (Table 2). The metrics computed at the voxel scale included changes in point density and maximum z value. These metrics were considered because it was believed that they would provide information on the changes in structure and height of vegetation in response to the burn event. The metric maximum z value computed at the scale of a voxel use the height factor (z-value) which is thought to be sensitive to structural changes after the burn. This is because the z-value corresponds to the height of the 3-D point return. After the burn, because of the absence of vegetation, the z-value will be affected the most. These metrics are described in Table 2 indicating the scale at which they were applied and the formula used to compute each of those metrics. Change refers to the difference between the two LiDAR scans i.e. pre- and post-burn for those metrics. It was hypothesised that point density following the burn would decrease within the voxels because of the absence of grasses and other vegetation. It was expected that the maximum-z value within voxels would be higher before the burn because of the presence of vegetation.

The volume metric was computed using the 'Volume Calculation Tool' within the Trimble LiDAR processing software, RealWorks Survey Advanced (version 6.4). This particular tool allows calculation of the volume between a point cloud and a plane (RealWorks, 2009). The arbitrary plane was selected as being normal to the Z-axis. It was then offset by 5m and kept constant so that the volume was calculated from the same distance each time. This metric was computed for the entire plot.

The volume metric derived for the two surface fuel layers was also expected to decrease following the burn due to the fire consuming grasses and litter close to the surface of the earth. As described in the formulae listed in table 2, Percentage Change (% change) for all the metrics were normalised with the pre-burn measures.

The mean and Standard Deviation (SD) was calculated from all the voxels within 5m and more than 5m away from the ground-LiDAR setup. To interpret results from the volumetric analysis, only the difference between volumes was computed and expressed as a % change as compared to pre-burn measures.

Table 2: Normalised metrics used to detect structural changes in the burned landscape using TLS data.

Metric	Scale	Definition	Formula
Point density	Voxel	Change in the number of points per unit volume of the voxel	$\text{Point density} = \frac{\text{Point Count}}{\text{Voxel Dimensions}}$ $\% \text{ Change} = \left( \frac{\text{Point Density}_{\text{Preburn}} - \text{Point Density}_{\text{Postburn}}}{\text{Point Density}_{\text{Preburn}}} \right) \times 100$

Maximum-z value	Voxel	Change in the maximum height value recorded in a voxel	$\% \text{ Change} = \left( \frac{\text{Maximum Z value}_{\text{Preburn}} - \text{Maximum Z value}_{\text{Postburn}}}{\text{Maximum Z value}_{\text{Preburn}}} \right) \times 100$
Volume	Plot	Change in the surface volume comprising near-surface & surface fuel layers	$\% \text{ Change} = \left( \frac{\text{Volume}_{\text{Preburn}} - \text{Volume}_{\text{Postburn}}}{\text{Volume}_{\text{Preburn}}} \right) \times 100$

## Results

Mean and SD values for the percentage change in point density and maximum-z value calculated from the voxels within 5m and more than 5m away from the ground-LiDAR setup are shown in figures 4 and 5 respectively. Results obtained from the changes in volume in the near-surface and surface fuel layer are shown in figure 6. Plot 2 (P2) was the control (unburnt).

The percentage change in point density after the burn observed is minimal for the control plot when voxels both within and more than 5m away from the TLS setup are considered. The associated SD values are also significantly lower as compared to the plots which received different fire treatments. In these plots, large and overlapping SD values are observed. The mean percentage change in point density does not seem to follow a trend in these burnt plots apart from the fact that it has increased after the burn. When the metric maximum-z value is considered, the mean and SD value for control tends to be very small when they are computed from voxels within 5m from the ground-LiDAR setup. When the voxels from more than 5m from the ground-LiDAR setup are considered, an increase in the mean value is observed with a significant increase in the SD value. For the other plots which were burnt, very high and overlapping SD values are observed in both the cases (within and more than 5m from the TLS setup). Although the percentage change in maximum-z value observed for the plots burnt is higher relative to the control (P2), the observed change is very small and is in the order of ~0.2%.

The percentage change in volume was the least in P2 which was unburnt. It recorded a 1% change as compared to a maximum of 5.86% change in P4. P1 and P3 showed similar changes in volume with a % change in volume of about 2.5%.

## Discussion

As the results have indicated, the mean percentage change in point density between burnt and unburnt plots is statistically insignificant with large and overlapping SD values. It was expected that the point density would decrease following the burn due to the vegetation in the near-surface fuel layer and litter in the surface fuel layer being consumed by the fire, but the results seem to suggest otherwise. As evident from the graph presented in figure 4, the point density has increased in all the plots that received different fire treatments although the magnitude of change does not seem to suggest any trends.

One possible explanation for this is that since ground and non-ground (vegetation, coarse woody debris) points were not separated, the corresponding change in point density is not seen as significant between burnt and unburnt plots. The pre-burn point density which was contributed by the presence of vegetation remained somewhat unchanged or even increased because the change in the point density due to the vegetation being burnt was compensated for by the point returns from the exposed ground.

It is thus believed that the changes in point density would give a more meaningful result once ground points are separated from non-ground points. This is also probably the reason for the lower SD values for P2 as compared to the burnt plots since nothing significantly changed in the landscape with the possible exception of branches, twigs and leaves falling from the trees. Additionally, histograms of changes in point density at different heights within 1m from the ground in voxels is expected to provide more information on where the point density has changed in the vertical column and by how much. This approach will enable computing absolute change in the surface and near-surface fuel layer because of the fire. A similar metric was derived in a study by White and Dietterick (2012). They derived change in canopy cover in response to a fire event by calculating the ratio of LiDAR returns falling above 1m, divided by the total number of returns for that voxel. It is expected that point density would be higher much closer to the ground in voxels which were burnt as compared to unburnt voxels. This is to be expected because after the vegetation has been burned, the underlying ground surface will be exposed leading to an increase in the point density.

Another approach would be to separate the ground and non-ground points based on generating a Digital Elevation Model (DEM) from the acquired ground-LiDAR data. Once this is achieved it would enable computing absolute change in near-surface and surface fuel layers in response to the burn event.

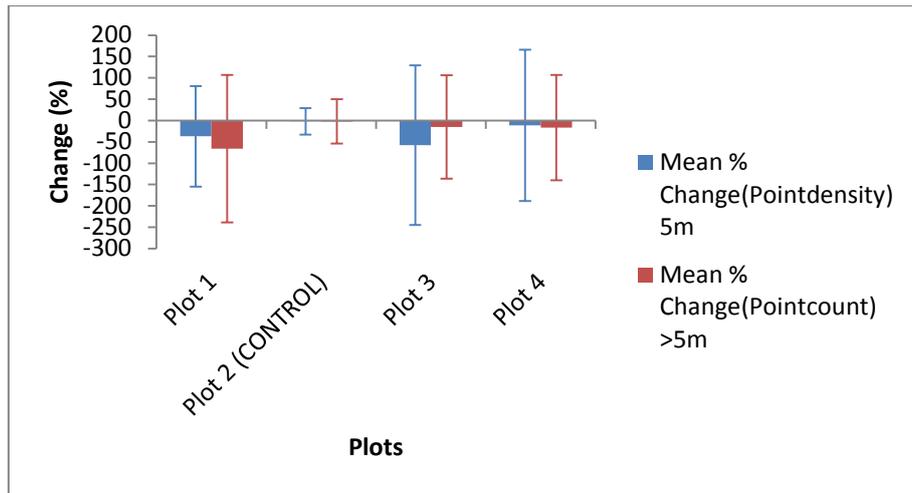


Figure 4: Percentage change in point density pre- and post-burn for voxels within and more than 5m away from the TLS setup. The blue and red bars represent the standard deviation values.

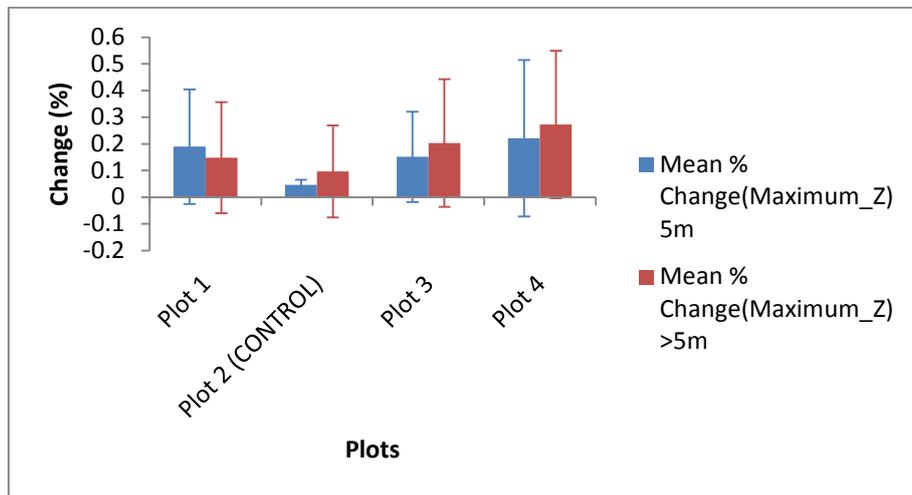


Figure 5: Percentage change in maximum-z value pre- and post-burn for voxels within and more than 5m away from the TLS setup. The blue and red bars represent the standard deviation values.

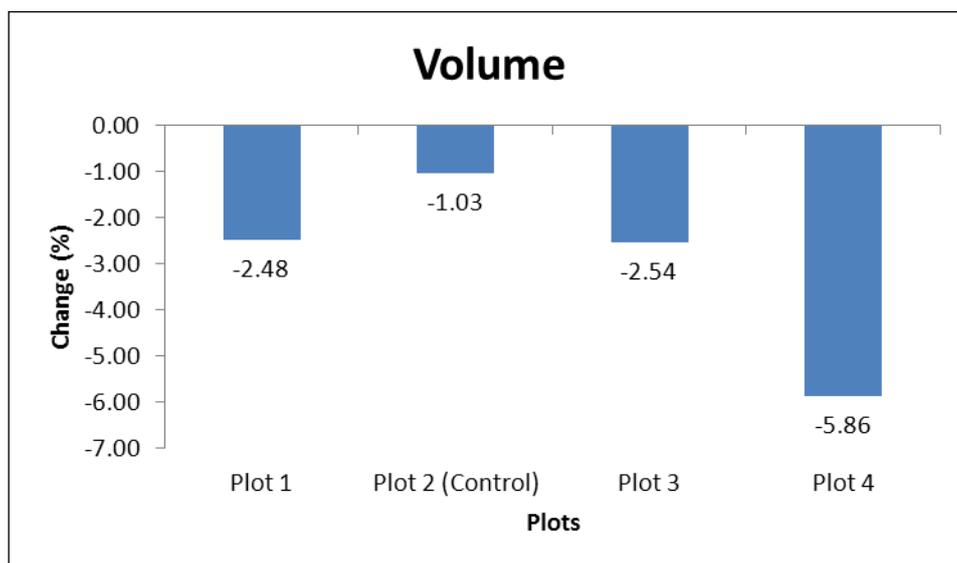


Figure 6: Percentage change in volume pre-and post-burn at the plot scale. Plot 2 is the control which remained unburnt).

The relative change observed in maximum-z value is minimal and the relatively large and overlapping SD values between burnt and unburnt plots makes this change insignificant as observed in figure 4. The overall observed change is very small because of the vector shift which was applied while pre-processing 3-D point cloud data. The vector shift is essential and needs to be applied to ensure none of the points in the x, y and z axes possess a negative value. The change in maximum-z value in voxels pre- and post-burn is very small (less than 1cm) and the percentage change is calculated relative to an inflated height datum (the pre-burn maximum-z value of at least 95m). This is the reason why the percentage change in maximum-z value between burnt and unburnt plots is not that significant. However, what is noteworthy is that despite the inflated height datum against which this metric was computed, TLS is sensitive enough to pick subtle changes in the landscape.

The results of the % change in volume in the plots after the burn are not that significant. Volumes of fuel consumed should vary depending on the types of fire treatments given to the plots. A maximum change in volume within 1m from the ground was recorded for P4 at 5.86%. However, this change in volume is quite large as compared to a 1% change in the unburned plot. It is believed that once the DEM is obtained, it will also enable investigation into the volume of fuel consumed in the near-surface and surface fuel layer as a result of the prescribed burn event. It is expected that this analysis would improve measures of change in fuel volumes after the ground- and non-ground points have been separated.

Although a few studies have been carried out in the past which have looked at applying LiDAR (both ALS and TLS) in burnt landscapes, most of them have looked at determining vertical vegetation profiles and canopy heights to model forest loss due to fire (e.g. Angelo et al., 2010, Heo et al., 2008, Wulder et al., 2009). The research findings presented here are quite different as compared to these studies. However, the study conducted by Rowell and Seielstad (2012) is quite similar in terms of the experimental setup and data acquisition using a TLS. However one major difference is with the metrics discussed which are quite different from the ones considered in the research presented here. It is proposed to investigate the utility of these metrics in the context of this study.

Further data analysis needs to be carried out which would involve computing histograms of point density at different heights within the voxels to quantify absolute change in the near-surface and surface layer due to the burn. Generating a DEM from the obtained LiDAR data would enable separation of non-ground points from ground-points which could further enhance analysis and interpretation of some of the metrics discussed in this paper. It would also enable computing much more accurate estimates of volumes of fuels consumed in plots which were given different fire treatments.

It is also believed that a few more metrics taking the z-value into consideration will also need to be explored. Few metrics proposed are changes in average z value and range of z value. Change in average z value would be defined as the change in the average height value recorded from heights of all the point returns within a voxel. Change in range of z value would be defined as the change in the difference between maximum and minimum height recorded in a voxel. It is believed that issues around inflated height datum as reported in this paper will be negated by using the range of z value metric.

## Conclusion

The primary objective of this paper was to report on how a ground-based LiDAR system may be used to detect changes in burned landscapes in the near-surface and surface fuel layer at both fine (voxel) and coarse (plot) scale using metrics derived from the 3-D point cloud data. Results from this research demonstrate the potential of a ground-LiDAR system to detect changes in burnt landscapes at both the fine and coarse scales. At the voxel scale, % change in range of z values best discriminated between burned and unburned landscapes (up to 40%). The metric, % change in average-z value was the best at discriminating the plots which were given different fire treatments while the range metric best differentiated between burned and unburned landscapes. At the plot scale, volume estimates seemed to suggest subtle differences between plots with different fire treatments. Although results reported in this research indicate very small changes between burned and unburned landscape, it does demonstrate the sensitivity of a TLS to detect those very subtle structural changes in the vegetation in response to the prescribed burn event. That said, in the event of catastrophic wildfires, the ability of a TLS to detect and quantify the changes will be much more significant.

Future work is needed to investigate comparisons of TLS metrics with traditional field estimates of fuel hazard and fire severity. This would also enable better interpretation of the derived metrics. Fuel hazard and burn severity assessment take into consideration vegetation and leaf-litter cover before and after the burn and provide a qualitative assessment of change because of the burn event. These field assessments are routinely carried out by land managers and fire management authorities in Victoria. It is felt that TLS data will also help better analyse and interpret the trends observed in the metrics discussed in this paper. Since in this paper, an attempt was made at demonstrating the applicability of a TLS to detect changes in burned landscapes at a local scale, it is felt that new methods and techniques will need to be developed which would enable its application at a landscape scale. Land managers will have to work with metrics beyond the scale of a voxel.

## Acknowledgements

The authors would like to thank Mr. Mohsen Laali for providing help with scripting in python for the pre-processing of TLS data.

## References

- Angelo, J. J., Duncan, B. W. & Weishampel, J. F. 2010. Using Lidar-derived vegetation profiles to predict time since fire in an oak scrub landscape in East-Central Florida. *Remote Sensing*, 2, 514-525.
- Bowman, D. M. J. S., Balch, J. K., Artaxo, P., Bond, W. J., Carlson, J. M., Cochrane, M. A., D'Antonio, C. M., DeFries, R. S., Doyle, J. C. & Harrison, S. P. 2009. Fire in the Earth system. *science*, 324, 481-485.
- Chen, X., Zhu, Z., Ohlen, D., Huang, C. & Shi, H. 2008. Use of multiple spectral indices to estimate burn severity in the Black Hills of South Dakota. Pecora 17—The future of land imaging... going operational, Denver, Colorado. ASPRS (American Society for Photogrammetry and Remote Sensing).
- Danson, F. M., Hetherington, D., Morsdorf, F., Koetz, B. & Allgower, B. 2007. Forest canopy gap fraction from terrestrial laser scanning. *IEEE Geoscience and Remote Sensing Letters*, 4, 157-160.
- Davies, D. K., Ilavajhala, S., Wong, M. M. & Justice, C. O. 2008. Fire information for resource management system: Archiving and distributing MODIS active fire data. *IEEE Transactions on Geoscience and Remote Sensing*, 47, 72-79.
- DSE 2010. *Overall fuel hazard assessment guide*, Department of Sustainability and Environment.
- Fernandes, P. M. & Botelho, H. S. 2003. A review of prescribed burning effectiveness in fire hazard reduction. *International Journal of Wildland Fire*, 12, 117-128.
- Gill, A. M. 1975. Fire and the Australian flora: a review. *Australian Forestry*, 38, 4-25.
- Gill, A. M. 1999. Biodiversity and bushfires: an Australia-wide perspective on plant-species changes after a fire event. In: Gill, A. M., Woinarski, J. & York, A. (eds.) *Australia's Biodiversity—responses to fire*. Environment Australia Biodiversity.
- Golson, J. 1972. The remarkable history of indo-pacific man. *The Journal of Pacific History*, 7, 5-25.
- Heo, J., Park, J. S., Song, Y. S., Lee, S. K. & Sohn, H. G. 2008. An integrated methodology for estimation of forest fire-loss using geospatial information. *Environmental monitoring and assessment*, 144, 285-299.
- Huang, H., Gong, P., Cheng, X., Clinton, N., Cao, C., Ni, W., Li, Z. & Wang, L. 2008. Forest structural parameter extraction using terrestrial LiDAR. Proceedings of SilviLaser 2009, 14-16 October, 2009, Texas, USA.
- Jupp, D. L. B., Culvenor, D. S., Lovell, J. L., Newnham, G. J., Strahler, A. H. & Woodcock, C. E. 2009. Estimating forest LAI profiles and structural parameters using a ground-based laser called 'Echidna®'. *Tree Physiology*, 29, 171-181.
- Lentile, L. B., Holden, Z. A., Smith, A. M. S., Falkowski, M. J., Hudak, A. T., Morgan, P., Lewis, S. A., Gessler, P. E. & Benson, N. C. 2006. Remote sensing techniques to assess active fire characteristics and post-fire effects. *International Journal of Wildland Fire*, 15, 319-345.
- Lentile, L. B., Morgan, P., Hudak, A. T., Bobbitt, M. J., Lewis, S. A., Smith, A. & Robichaud, P. R. 2007. Post-fire burn severity and vegetation response following eight large wildfires across the western United States. *Fire Ecology*, 3, 91-108.
- Loudermilk, E. L., Hiers, J. K., O'Brien, J. J., Mitchell, R. J., Singhanian, A., Fernandez, J. C., Cropper, W. P. & Slatton, K. C. 2009. Ground-based LIDAR: a novel approach to quantify fine-scale fuelbed characteristics. *International Journal of Wildland Fire*, 18, 676-685.
- Loudermilk, E. L., Singhanian, A., Fernandez, J. C., Hiers, J. K., O'Brien, J. J., Cropper Jr, W. P., Slatton, K. C. & Mitchell, R. J. 2007. Application of ground-based LIDAR for fine-scale forest fuel modeling. Proceedings of USDA Forest Services. USDA Forest Service Processing RMRS-P-46CD.
- Martín, M. P., Díaz-Delgado, R., Chuvieco, E. & Ventura, G. 2002. Burned land mapping using NOAA-AVHRR and TERRA-MODIS. In: Viegas, D. X., ed. IV International Conference on forest fire research. 2002 Wildland Fire Safety Summit, Luso, Coimbra, Portugal. Millpress.
- Miller, J. D. & Thode, A. E. 2007. Quantifying burn severity in a heterogeneous landscape with a relative version of the delta Normalized Burn Ratio (dNBR). *Remote Sensing of Environment*, 109, 66-80.
- Moskal, L. M. & Zheng, G. 2011. Retrieving Forest Inventory Variables with Terrestrial Laser Scanning (TLS) in Urban Heterogeneous Forest. *Remote Sensing*, 4, 1-20.
- Norton, J., Glenn, N., Germino, M., Weber, K. & Seefeldt, S. 2009. Relative suitability of indices derived from Landsat ETM+ and SPOT 5 for detecting fire severity in sagebrush steppe. *International Journal of Applied Earth Observation and Geoinformation*, 11, 360-367.
- Pereira, J. M. C., Chuvieco, E., Beaudoin, A. & Desbois, N. 1997. Remote sensing of burned areas: a review. In: Chuvieco, E. (ed.) *A review of remote sensing methods for the study of large wildland fires*.
- RealWorks 2009. *Trimble RealWorks 6.4 User Manual*.
- Rogan, J. & Yool, S. R. 2001. Mapping fire-induced vegetation depletion in the Peloncillo Mountains, Arizona and New Mexico. *International Journal of Remote Sensing*, 22, 3101-3121.
- Rowell, E. & Seielstad, C. 2012. Characterising grass, litter, and shrub fuels in longleaf pine forest pre- and post-fire using terrestrial LiDAR. SilviLaser 2012, 16-19 September, 2012, Vancouver, Canada. 1-8.

- Silva, J., Sa, A. C. L. & Pereira, J. M. C. 2005. Comparison of burned area estimates derived from SPOT-VEGETATION and Landsat ETM+ data in Africa: Influence of spatial pattern and vegetation type. *Remote Sensing of Environment*, 96, 188-201.
- Solans Vila, J. P. & Barbosa, P. 2009. Post-fire vegetation regrowth detection in the Deiva Marina region (Liguria-Italy) using Landsat TM and ETM+ data. *Ecological Modelling*, 221, 75-84.
- Soverel, N. O., Perrakis, D. D. B. & Coops, N. C. 2010. Estimating burn severity from Landsat dNBR and RdNBR indices across western Canada. *Remote Sensing of Environment*, 114, 1896-1909.
- Teobaldelli, M., Zenone, T., Puig, D., Matteucci, M., Seufert, G. & Sequeira, V. 2007. Structural tree modelling of aboveground and belowground poplar tree using direct and indirect measurements: terrestrial laser scanning, WGROGRA, AMAPmod and JRC-3D Reconstructor. In: Prusinkiewicz, P. & Hanan, J., eds. Proceedings of 5th International Workshop on Functional Structural Plant Models, 4-9 November, 2007, Napier, New Zealand. 4-9.
- Thies, M. & Spiecker, H. 2004. Evaluation and future prospects of terrestrial laser scanning for standardized forest inventories. ISPRS Working Group VIII/2: Laser-Scanners for Forest and Landscape Assessment, Freiburg, Germany. 192-197.
- Van Wagtenonk, J. W., Root, R. R. & Key, C. H. 2004. Comparison of AVIRIS and Landsat ETM+ detection capabilities for burn severity. *Remote Sensing of Environment*, 92, 397-408.
- Watt, P. J. & Donoghue, D. N. M. 2005. Measuring forest structure with terrestrial laser scanning. *International Journal of Remote Sensing*, 26, 1437-1446.
- Watt, P. J., Donoghue, D. N. M. & Dunford, R. W. 2003. Forest parameter extraction using terrestrial laser scanning. Proceedings of ScandLaser Scientific Workshop on Airborne Laser Scanning of Forests, Umeå, Sweden. 237-244.
- White, R. A. & Dieterick, B. C. 2012. Use of LiDAR and multispectral imagery to determine conifer mortality and burn severity following the lockheed fire. In: Standiford, R. B., Weller, T. J., Piirto, D. D. & Stuart, J. D., eds. Proceedings of coast redwood forests in changing California: A symposium for scientists and managers, Albany, California, USA. Pacific Southwest Research Station, Forest Service, U.S. Department of Agriculture, 667-675.
- Wulder, M., White, J., Alvarez, F., Han, T., Rogan, J. & Hawkes, B. 2009. Characterizing boreal forest wildfire with multi-temporal Landsat and LIDAR data. *Remote Sensing of Environment*, 113, 1540-1555.