Effect of thinning and burning fuel reduction treatments on forest carbon and bushfire fuel hazard in *Eucalyptus sieberi* forests of south-eastern Australia

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Abstract

More frequent hot and windy weather in fire prone forested landscapes requires that a full suite of fuel reduction measures be investigated for effectiveness in fuel hazard reduction, environmental impact and carbon (C) outcomes. Although prescribed fire and thinning are routinely applied in forests of North America to reduce fuel loads, there are few detailed studies from Australia. We report the impacts of fuel reduction treatments including burning, mechanical thinning and the combination of both on forest C and fuel hazard in open forests dominated by *Eucalyptus sieberi* in south-eastern Australia. Carbon losses to the atmosphere and redistribution within the forest were calculated from stocks within each fuel category before and after treatment. Mechanical thinning + burning was the most effective treatment for reducing aboveground C and fuel hazard, with major reductions in dead trees, stumps and understorey, as well as stems removed for sale as pulpwood. However forest floor fuel loads increased in thinned treatments relative to control forests. The overall fuel hazard rating in the burn only treatment was significantly reduced from extreme to low immediately following burning. In thinned only stands, the overall fuel hazard rating did not change from the pre-treatment rating of extreme, due to high surface and forest floor fuel loads and loose and flammable bark on the retained overstorey trees. This result suggests the current fuel hazard guide in use in Australia should be revised to enable it to better describe the benefits of thinning for fuel reduction - in this case the removal of about 50% of aboveground C mostly as overstorey trees, and a significant reduction in understorey, dead trees and stumps.

Keywords (6–12 key words/phrases): planned fire, mechanical fuel reduction, thinning, bushfire fuel hazard assessment, bark, stumps, forest floor

1. Introduction

Treatments to reduce fuels and the risk of wildfire are widely applied in forests around the world, especially in seasonally dry forests, such as those of southern Europe and North America (Stephens et al., 2012; Ubeda et al., 2018). In Australia, one of the most fire prone continents on earth, the temperate forests burn frequently in fires ignited by lightning strikes or increasingly by anthropogenic sources (Williams et al., 2009). The regeneration of *Eucalyptus* forests occurs quickly after fire, with overstorey trees generally re-sprouting to re-establish the canopy as well as regenerating from seed. Since the mid-1950s land managers have used prescribed burning, usually at 20 to 30 year intervals, to reduce fuels and the severity of wildfires, as well as increase the chances of effective wildfire suppression (McCaw, 2013; Penman et al., 2011). However due to the impact of prescribed fires on air quality and the potential for threats to humans, animals and property through fire escape, there is increasing social and economic pressure to find alternatives to burning for fuel reduction (Ximenes et al., 2017). Furthermore the increase in extreme fire danger weather over recent years, due to changing climate, has resulted in a greater risk of wildfires for the continent (Fairman et al., 2016; Lucas et al., 2007). Other factors adding to the complexity of implementing safe burning practices are the relatively short window of appropriate weather conditions for safe burning, and the logistics and expense of managing and maintaining human and machine resources to treat vast areas of land annually (McCaw, 2013).

Alternatives to prescribed burning include mechanical fuel reduction, including commercial thinning to remove tree stems and flatten the understorey, or vegetation mastication that involves grinding, shredding or chopping vegetation into small chunks that are either left on site or removed. Often mechanical fuel reduction is followed by burning to reduce high surface fuel loads created by mechanical operations. A number of studies have investigated the effectiveness of mechanical thinning in reducing wildfire risk in North America (Butler et

al., 2013; Mason et al., 2007; Wilims et al., 2017) and Mediterranean Europe (Fernandez et al., 2015; Mirra et al., 2017; Pique and Domenech, 2018). The impact of mechanical thinning on fire propagation and fuel hazard has also been investigated in a limited number of studies in south-eastern Australia (Proctor and McCarthy, 2015; Volkova et al., 2017). Results from these studies indicate that a combination of thinning and burning is the most effective treatment for reducing fire severity (Kalies and Kent, 2016), and this is likely to be the case for Australian *Eucalyptus* forests. However the impact of different fuel reduction treatments on forest C remain largely under-studied. Typically fire reduces aboveground forest C by consuming forest floor residues, with litter and deadwood the most affected (Bennett et al., 2014). Tree bark is also an important contributor to C loss and emission (Gill et al., 1986; Schuur et al., 2003; Volkova et al., 2014). The effect of fires on overstorey trees, the largest aboveground C pool, is usually through C redistribution from the live to dead pool rather than C loss to the atmosphere (Stephens and Moghaddas, 2005b; Volkova and Weston, 2013; Volkova and Weston, 2015). Prescribed fire increases soil C due to production of pyrogenic C and its incorporation into soil profile (Krishnaraj et al., 2016; Santin et al., 2016). The few studies of C loss from thin + burn treatments are mainly from North American forests (Kalies et al., 2016; Reinhardt and Holsinger, 2010; Stephens et al., 2009; Winford and Gaither, 2012). These studies show that a combination of thinning + burning leads to the greatest C loss whilst also increasing forest resilience to wildfires in the long term (McIver et al., 2013; Stephens et al., 2009).

A study of *Eucalyptus* forests in the Australian states of Western Australia, New South Wales and Victoria was implemented in 2016 to determine if mechanical thinning can reduce bushfire risk in an economical, socially acceptable and environmentally sound manner around key assets, such as conservation areas or townships, where prescribed burning is undesirable

(Ximines et al. 2017). Our study of *E. sieberi*-dominated forests in Victoria, reported here, is a part of the larger mechanical fuel reduction trial described above.

The aim of this study is to determine the impact of the fuel reduction treatments of burning, thinning and thinning + burning in open forest dominated by *Eucalyptus sieberi* (L.A.S Johnson) on the distribution of forest C and on bushfire fuel hazard. We hypothesized that both the thinning alone and the thinning + burning treatments would be at least as effective as burning in reducing fuel hazard immediately following treatment. *E. sieberi*, a major commercial timber species (ABARES, 2013), dominates open forest formations that are widespread in south-eastern Australia; occurring in Tasmania, Victoria and New South Wales (Boland et al., 1984). Furthermore, the structure of *E. sieberi* forests is typical of open forests more generally, so that studies of these forests provides insights into the potential applicability of mechanical fuel reduction for southern Australian forests.

2. Methods

2.1. Study sites

Open forests dominated by *E. sieberi* in the east Gippsland region of south-eastern Australia were selected for the trial; the location in the state of Victoria is shown in Fig 1. The forests are predominantly even-aged regrowth from extensive wildfires in 1983, that was followed by salvage-logging that removed stems of commercial value, leaving a small number of older and much larger trees consisting mainly of *E. obliqua* L'Herit. At the time of the measurements in 2016-2018, the forests had not been burnt since their regeneration, mainly from seed, 35 years ago in 1983. The trial was established in three replicates of four treatments – mechanical thinning (M), mechanical thinning followed by burning (M+B), burning only (B) and an untreated or control (CT). Among the three replicates, each of about 40 ha, the thinned treatments were assigned to the plots closest to the access road to minimize the cost of access track construction and log extraction, as shown in Fig. 1. To characterize

forest C and fuels in each treatment, measurements of aboveground biomass, soil C (to 10 cm depth) and fuel hazard were made in 0.04 ha circular plots (depending on slope, radius varies from 11.28 m to 12.12 m), summing to a total of 240 plots (3 replicates x 4 treatments x 20 plots). Plot locations were assigned *a priori* using a grid method, with plot centres within a treatment about 60 to 70 meters apart (Fig. 1).

2.2. Treatments

Four treatments were imposed as follows: (1) Mechanical thinning (M) – trees were thinned using a bay and out-row method, where out-rows were no wider than 4.5 m to allow for the removal of larger trees, while the retained bays were approximately 12 m wide. The target basal area removal was 50%; (2) Mechanical thinning and Burning (M+B) – following thinning, as described above, prescribed burning was applied to reduce forest residues; (3) Burning (B) – fuels were reduced using prescribed burning, and (4) Control (CT) – no treatment was applied.

2.3. Sampling design

2.3.1. Aboveground and soil carbon

Within each 0.04 ha sampling plot, the diameter at breast height (dbh) and species identity were recorded for every overstorey tree (dbh ≥10 cm) with green foliage. Dead trees, including stumps were identified as those with no green foliage, curving trunks and a lean from the vertical; these were measured for dbh, and where possible species identified from bark characteristics. An estimate of C present in large old stumps was derived from measures of their diameter, height and degree of rottenness. Within each plot three representative overstorey trees were measured for tree height using a Vertex III laser rangefinder (Haglof, Sweden). Understorey trees, defined as those with dbh <10 cm, were measured for dbh, live

or dead status and species, as described above, in a circular sub-plot of 0.004 ha nested within each plot.

Coarse woody debris (CWD), defined as branches and logs with a diameter ≥2.5 cm lying on the forest floor and detached from standing trees were measured using the line intercept method of Van Wagner (1968). Three randomly selected plots within each treatment in each replicate were sampled to yield a total of 36 transects (3 replicates x 4 treatments x 3 plots). A 100 m transect was established from the centre point of a plot and oriented north for the first 50 m, followed by 50 m east. All CWD were measured at the point of intersection perpendicular to the transect and each was assigned to one of three decay classes: class 1 (sound), class 2 (outer layers and sapwood showing signs of decomposition) and class 3 (signs of decomposition extended to heartwood). CWD from a range of diameters and decay classes was sampled to determine moisture by oven drying to 100°C and density by a water displacement method (Supplementary, Table A1). Due to the very high occurrence of wood residues on the ground after mechanical treatments (M, M+B) only the first 50 m north transect was resampled and subsequently compared with the corresponding pre-treatment 50 m north transect.

Surface fuels, including live and dead plant material such as leaves, bark, fruits (woody capsules) and small branches <6 mm on the forest floor, and twigs with d<2.5 cm were sampled within a metal ring of 0.1 m^2 placed on the forest floor in each of the plots. At every second plot, after removal of surface fuels from the metal ring, the decomposing organic residues not incorporated into the mineral soil were sampled to yield the forest floor fuel category. Following treatments, large amounts of bark, woody residues and charred organic residues created during burning were included in this fuel category. All surface and forest floor fuel samples were oven dried to 100°C for at least 48 hours prior to further analysis.

Soil to 10 cm depth was sampled volumetrically from 0-5 cm and from 5-10 cm depths using a soil core of 204 cm^3 volume, at the same plots as CWD measurements (36 plots sampled for soil). Samples were transferred to the laboratory, sieved through a fine mesh (2.5 mm) to remove stones and roots that were excluded from the analysis. Soil was oven dried at 105°C for at least 24 hours.

2.3.2. Overall fuel hazard and canopy cover assessment

The fuel hazard assessment guide (Hines et al., 2010) was used to assess fuel hazard at each plot by assigning an overall fuel hazard rating (OFHR). Within a 5-10 m radius from each plot centre point all fuels (surface, near-surface, elevated and bark) were visually assessed, including the height and cover of near-surface and elevated fuels and surface fuel depth, estimated from 3-5 litter depth measurements. The visual ratings for each fuel category were then summed to give rise to an overall fuel hazard rating (OFHR) as described by Hines et al. (2010).

At the centre of each plot, canopy cover (%) was estimated by looking up and visually placing the canopy into a class using 5% increments following the methodology of McDonald et al. (1990).

2.4. Estimating biomass and fuel loads

2.4.1. Estimating tree biomass

Overstorey tree biomass (dbh≥ 10 cm) was estimated using a set of additive allometric equations (Bi et al., 2004) for each species of live trees, with dbh as the only independent variable. In the few cases where tree species was not identified, an allometric equation for the dominant species was applied. The dead tree biomass was estimated using the same additive allometric equation but excluding the tree foliage component. The biomass of stumps was estimated as the volume of a cylinder multiplied by wood density for class 1, and accounting

for the percent of rottenness. Understorey tree biomass (dbh< 10 cm) was estimated using the general allometric equation for small trees of Volkova et al. (2015). For the list of allometric equations used see Supplementary section.

2.4.2. Estimating CWD biomass

The volume of CWD was estimated following the method of Van Wagner (1968), volume was then converted to load (Mg ha^{-1}) using the CWD density derived from the water displacement method for each of the CWD decay classes (Table A1).

2.5. Carbon analysis

Subsamples of CWD and soil were ground to a fine powder and analysed for total C in a LECO Trumac (18. 6016TN/TC via Dumas Combustion - LECO Trumac).

The timeline for the application of treatments and subsequent collection of samples is given in Figure 2. A severe drought impacted east Gippsland throughout 2017 and delayed the burning of the trial until May 2018, or 12 months after what was originally planned. At the time of final sampling in June 2018, 20% of control plots (trees, CWD and litter depth) were re-measured.

2.6. Statistical analysis

A linear mixed model (LMM) was applied to test the effect of treatment, time and their interaction on each variable of interest (number of live/dead trees per hectare, overstorey Mg C ha^{-1}, understorey Mg C ha^{-1}, dead standing Mg C ha^{-1}, CWD Mg C ha^{-1}, surface and forest floor fuels Mg C ha^{-1}). The fixed factors were ‘Treatment’ (M, M+B, B, CT) and ‘Time’ (before, after treatment); ‘Site/Plot ID’ (Plot ID nested within Site) was used as the random part of the model. Post hoc tests were conducted to assess the significance of interaction contrast between the controls and other treatments. Specifically, they compare the before to after difference in controls to the before to after difference in the other treatments. For soil C,

variables of interest were soil Mg C ha^{-1} to 0-5 cm depth and 5-10 cm depth. The fixed factors also included soil depth. The differences were considered significant at 5% level.

For each analysis, normality and heterogeneity of variance were tested graphically using histograms of residuals and fitted value plots. Based on those visual assessments no transformations were required. The analyses were conducted in the R statistical environment version 3.6.0 (R Core Team, 2019) using the packages nlme v.3.1-140 (Pinheiro et al., 2019), emmeans v.1.3.4 (Lenth, 2019) and piecewiseSEM v.2.0.2 (Lefcheck, 2016).

3. Results

3.1. Forest carbon and fuel loads prior to treatments

The forest overstorey was dominated by *E. sieberi* which accounted for between 72% and 89% of all trees present, followed by *E. obliqua* (8% - 26%) and a minor presence of other species such as *E. consideniana* Maiden, *E. globulus* Labill. and *E. globoidea* Blakely (Table 1). Prior to the application of treatments all measured parameters were similar among the four treatments, with an average basal area (BA) for overstorey trees of 55 m^2 ha^{-1}, overstorey tree density in the range 1200-1600 trees ha^{-1} and canopy cover of about 40% (Table 1). All replicates carried dense understorey of *Acacia* species and sclerophyllous shrubs such as *Davesia spp,* (Fig. S1).

3.2. Effect of thin and burn treatments on forest carbon

3.2.1. Effect of thin and burn treatments on trees

The number of live and dead trees was significantly affected by each of the fuel reduction treatments (Table A2). Almost 80% of tree stems were removed in the M and M+B treatments, reducing the number of live overstorey trees to an average 263 trees ha^{-1} (Fig. 3A) and basal area to 23 m^2 ha^{-1}. Significant tree mortality of 170 trees ha^{-1} (or 12%) was observed after prescribed burning in B treatment (Fig. 3A). Fire further reduced the number

of dead trees in the M+B treatment (5±2 trees ha^{-1}) relative to the M treatment (19±4 trees ha^{-1}). In contrast, the number of dead trees in the B treatment increased by 56% to 106 trees ha^{-1} following burning (Fig. 3B).

Removal of overstorey trees for commercial purposes extracted an average 108 Mg C ha^{-1} from the M and M+B treatments (weighbridge data supplied by VicForests); the field measurements clearly show significant reduction of both overstorey and understorey C (Figs. 4A,B). Despite a large increase in the number of dead trees in the B treatment (Fig 3B), there was no significant change in dead standing C (Fig. 4C, Table A2). A large proportion of the dead standing biomass was contributed by large (dbh>80 cm) rotting stumps remaining from previous logging operations. These large stumps burnt for days and weeks and were either completely combusted in prescribed burning or greatly reduced in diameter – reducing C in the dead standing pool for the M+B treatment and cancelling the effect of an increased number of smaller in diameter dead trees in the B treatment (Figs. 3B and 4C, Table A2).

3.2.2. Effect of thin and burn treatments on CWD

A significant increase in CWD loads from 64.5 ±14.3 to 94.4±16.1 Mg C ha^{-1} was observed after mechanical thinning (Fig. 4D), with a greater increase in 100 h (from 47 to 82) than 1,000 h (14 to 25) size class categories. CWD loads remained high after burning in both the M+B and B treatments and while prescribed burning consumed about 30% of CWD (data not shown), the contribution of fallen-in trees during and immediately after burning to CWD loads resulted in no change in CWD pool for the B treatment (Fig. 4D, Table A2).

3.2.3. Effect of thin and burn treatments on surface and forest floor carbon

Thinning alone led to more than doubling of the surface and forest floor fuels from 8.18±0.62 Mg C ha^{-1} to 28.5±2.5 Mg C ha^{-1} due to the addition of tree residues, such as canopy foliage, branches and bark after thinning (Figs. 4E, F, Table A2). Applying burning to thinned sites

decreased surface fuel loads from 12.4±1.7 Mg C ha^{-1} to 5.63±0.98 Mg C ha^{-1} (Fig. 4E) and forest floor fuels from 7.2±0.5 Mg C ha^{-1} to 5.53±0.64 Mg C ha^{-1} (Fig. 4F). Conventional prescribed burning (B treatment) reduced surface fuels from 2.47± 0.18 Mg C ha^{-1} to 0.63±0.15 Mg C ha^{-1} (Fig. 4E) but increased the forest floor fuels from 7.69 ±0.66 to 10.53±0.95 Mg C ha^{-1} due to addition of charred forest residues (Fig. 4F).

3.2.4. Effect of thin and burn treatments on soil and total C

Prescribed burning of thinned sites did not affect soil C to 10cm depth, which remained at around 44.89±4.49 Mg C ha^{-1}, not significantly different from pre-fire values (Fig. 5). In the B treatment, a marginally significant reduction in the 0-5 cm soil C was compensated by a slight increase in 5-10 cm soil C (Table A2, Fig. 5).

The total pre-treatment forest C stock to 10 cm soil depth (excluding coarse roots) was about 362 Mg C ha^{-1} (Figs. 4 and 5). No C loss to the atmosphere was observed in the mechanical only treatment, with the decrease in overstorey pool due to removal of stems for commercial purposes and redistribution to other pools such as CWD, surface and forest floor fuels. Loss of C in the M+B treatment was mainly due to combustion of dead standing trees while in the B treatment it was due to tree mortality (Fig. 3). The C loss in the B treatment varied greatly between replicates, reflecting the difference in fire characteristics during burning caused by contrasting weather and fuel moisture conditions as described below.

The experimental burns in this study were applied in both very dry and very moist conditions that resulted in widely different fuel reduction outcomes in the B treatment (Table 2). Due to very dry weather conditions, Replicate 3 (‘hot’ burn) was ignited in the late afternoon and was allowed to burn overnight. The burn resulted in complete combustion of the surface fuels with no unburnt patches, and tree scorching above 5 m (Fig. S1). Replicate 2 was burnt several weeks later (Fig. 2) after significant rainfall and in much milder conditions (‘mild’ burn). This milder burn scorched trees to heights varying between about 0.1-2 m (average

0.8m); the burn was patchy with incompletely combusted surface fuels at some plots and no ignition at six plots (the latter were excluded from the analysis).

The contrasting burn conditions influenced C loss and redistribution between replicates 2 and 3 of the B treatment. In the hot burn, 18.57±1.6 Mg C ha^{-1} was lost from overstorey C and 7.99 ±7.64 Mg C ha^{-1} was lost from dead standing pool due to the complete combustion of large stumps in the latter (Fig. 6). In the mild burn, overstorey C loss averaged 3.05±20.8 Mg C ha^{-1}. Increase in the CWD pool by 13.16±6.07 Mg C ha^{-1} was mainly due to redistribution from the dead standing pool which was reduced by 9.88±1.85 Mg C ha^{-1} (Fig. 6). Greater combustion of surface and forest floor fuels in the hot burn led to lower production of char residues compared to the mild burn (Fig. 6).

3.3. Effect of thin and burn treatments on fuel hazard ratings

The overall fuel hazard rating (OFHR) was reduced from extreme (E) to low (L) in thinned and burnt forest (M+B treatment, Table 3). In thinned only forests (M treatment) the hazard ratings for two of the four parameters contributing to the OFHR were reduced to low (L), yet remained extreme for bark and were increased from very high to extreme for surface fuels. Traditional prescribed burning (B treatment) reduced the OFHR from extreme to low (Table 3).

4. Discussion

The C losses of around 19 Mg C ha^{-1}in these *E. sieberi* forests from thinning + burning or burning alone are similar to losses reported for temperate forests of North America (Dore et al., 2016; Stephens and Moghaddas, 2005a; Stephens et al., 2009). Fire severity had a significant impact on C losses among replicates in the burn only treatment. It varied from 7 Mg C ha^{-1} for the mild burn - similar to previously reported losses from prescribed burning in *Eucalyptus* forests (Volkova and Weston, 2013; Volkova and Weston, 2015) to 30.4 Mg C ha^{-1} for the hot burn, a loss comparable to a wildfire scenario in a similar forest (Volkova et

al., 2014). Excluding C removed in harvested stems, the major loss of aboveground C in thinned and burnt forest was from standing dead trees and stumps and the removal of understorey trees. In both treatments, M+B and B, larger diameter stumps either smouldered away or were greatly reduced in diameter after burning. The recruitment of new stumps and dead trees of smaller diameter had no significant impact on the deadwood C pool. This is in contrast to findings of several other studies observing a reduction in large diameter stumps and dead trees after fires, with losses in the larger diameter classes of dead trees being offset by the creation of new smaller diameter class dead trees (Bagne et al., 2008; Stephens and Moghaddas, 2005b). In our study the remaining large tree stumps, a legacy of previous forest management, is an important component of the aboveground C stock, the fate of which is an important determinant of C balance after a thinning and burning treatment. The study also revealed no reduction in the CWD loads in thinned and burnt stands, despite an increase in the char-C content of CWD after fires, also a contrast to previously reported reductions in CWD of 100 h and 1000 h fuels (Stephens and Moghaddas, 2005a; Stephens and Moghaddas, 2005b). In contrast we observed an increase in CWD loads in all burnt treatments due to either contribution of freshly fallen trees of relatively small diameter (B treatment), or to low availability of CWD which was crushed and pressed into the ground by heavy machinery during thinning (M+B treatment). The decrease in 0-5 cm soil C after fire in the B treatment was compensated by an increase in C in 5-10 cm soil, suggesting a pulse of C redistribution or translocation down the soil profile as found by Krishnaraj et al. (2016).

No damage to the retained trees was observed in thinned and burnt stands despite burns conducted in autumn (March-May in the Southern hemisphere). This was in contrast to the results of a similar study in a *Eucalyptus* forest in south-western Australia (McCaw et al., 1997). The onset of an extended dry period delayed the burning of thinned treatments by about 12 months (Autumn 2017 until Autumn 2018) due to the danger of fire escape or

smouldering and subsequent re-ignition prior to hot and dry summer conditions. Despite this precaution, and possibly due to the extended dry conditions, when burning was completed areas of slash residue and stumps smouldered for several months, posing the risk of fire re-ignition. While we acknowledge that more time is required to allow for coppice regeneration to appear to more accurately determine tree mortality after burning, the low and minimal scorching of trees in the M+B treatment (Fig. S1) and the relatively high remaining litter loads (Figs. 4 E,F) suggest that tree damage was minimal. The overall fuel hazard rating (OFHR) was reduced from extreme (E) to low (L) in thinned and burnt forest (M+B treatment), suggesting that this treatment was at least as effective as conventional prescribed burning in reducing fuel hazard. While in the M treatment, bark fuels were reduced by half due to removal of almost 80% of the overstorey trees (or 50% of basal area), the bark fuel hazard rating remained ‘Extreme’ (after Hines et al., 2010), as there was minimal evidence of bark scorching and also the presence of large amounts of combustible bark deposited on the surface from the thinning operation. Because the bark fuels remained in the ‘Extreme’ range the overall fuel hazard rating (OFHR) was “Extreme” for this treatment. In this context, the OFHR assessment did not adequately capture the change in fuel condition resulting from thinning, as clearly the sharp reduction in elevated fuels and removal of about 50% of the overstorey trees and elevated bark is highly likely to have reduced the fuel hazard and also the propagation of fire. Here we support Penman et al. (2017) who advocate for the development of a multi-dimensional approach to better assess bark hazard and improve hazard assessments.

During burning of treatments we observed a reduction in fire severity in thinned and burnt treatments compared to the hot burnt treatment, mainly due to the absence of elevated fuels and the breaking of the vertical connectivity of fuels, similar to the findings of many studies in Northern America and Europe (Kalabokidis and Omi, 1998; Kent et al., 2015; Pique and

Domenech, 2018; Pollet and Omi, 2002; Restaino and Peterson, 2013). These aspects of treatment that impact on fire behaviour are the subject of a separate study. However, as the forest recovers over the coming years and decades, thinning is likely to result in the rapid regrowth of elevated and understorey fuels. The high intensity thinning (about 50% of basal area removal) in this study reduced canopy cover by about 50% (Table 3), allowing more light to penetrate to the forest floor that will eventually lead to faster regrowth of the understory and recovery of elevated fuels. In contrast, thinning at low intensity would keep the canopy closed allowing greater control of understory growth (Pique and Domenech, 2018). Thinning also has a greater probability of creating more favourable conditions for non-native plants than burning in the short-term and should be the subject of future investigation (Wilims et al., 2017). Additionally, *E. sieberi* can regenerate vigorously from coppice and little is known about the competition between coppice and retained trees following thinning, with regrowth rates affected by frequency of fires and site quality (Forrester et al., 2003).

5. Conclusion

This study provides new insight into the impact of fuel reduction treatment on C outcomes and fuel hazard for a range of fuel reduction treatments in south-eastern Australian *Eucalyptus* forests. Understanding how thin and burn fuel reduction treatments affect forest C, vegetation structure and fuel characteristics is necessary for making informed decisions to meet management objectives. In windy and dry conditions the dense shrubby understorey and surface fuels of these *Eucalyptus*-dominated forests burns quickly. Extreme weather and high winds can lead to explosive fire conditions with running crown fires and spotting well ahead of the flame front. To safeguard communities and assets in close proximity to these highly flammable forests, treatment with mechanical thinning followed by burning of residues was at least as effective as a conventional prescribed burning. The benefits of a thin and burn

treatment are likely to persist for up to 7 to 10 years prior to recovery of fuels to untreated status.

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Figures

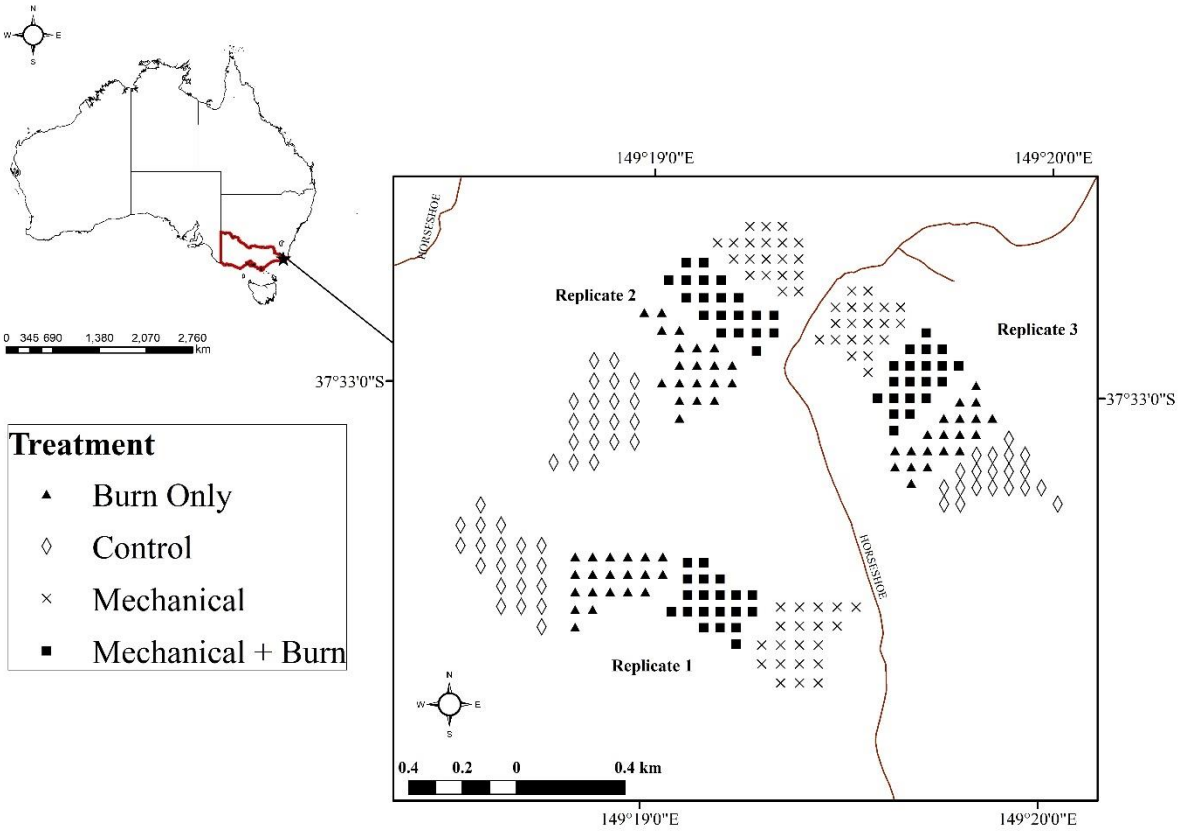

Figure 1. Location of the study sites in south-eastern Australia and the experimental design layout. Where: Control - open diamond; Mechanical - cross, Mechanical + Burn – solid square; Burn – solid triangle up.

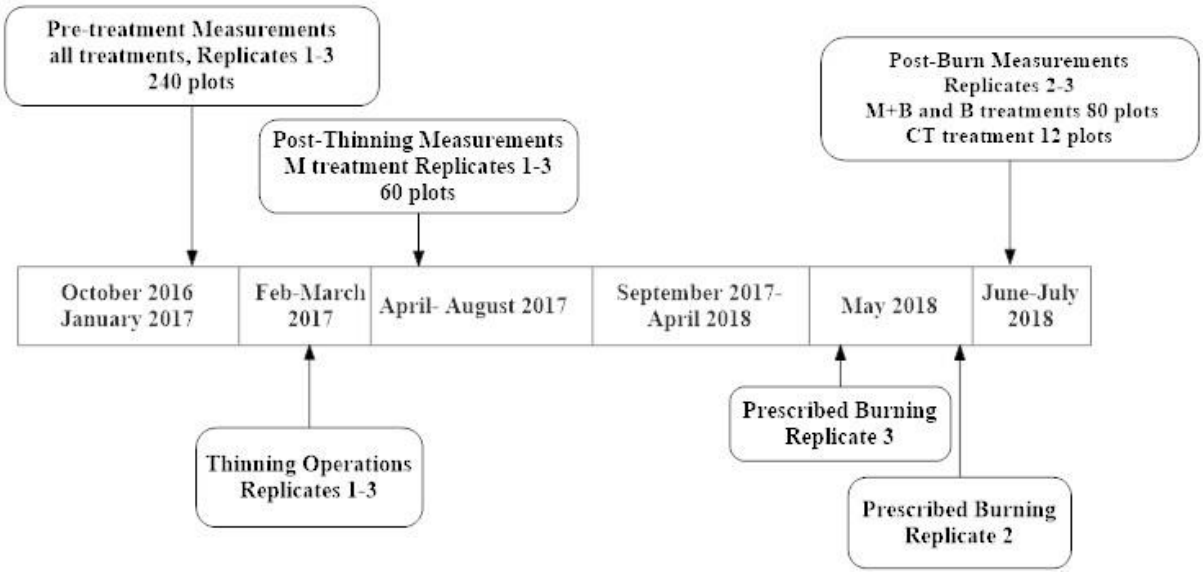

Figure 2. Chronogram showing the sequence of measurements, imposition of treatments and re-measurement throughout 2016 to 2018.

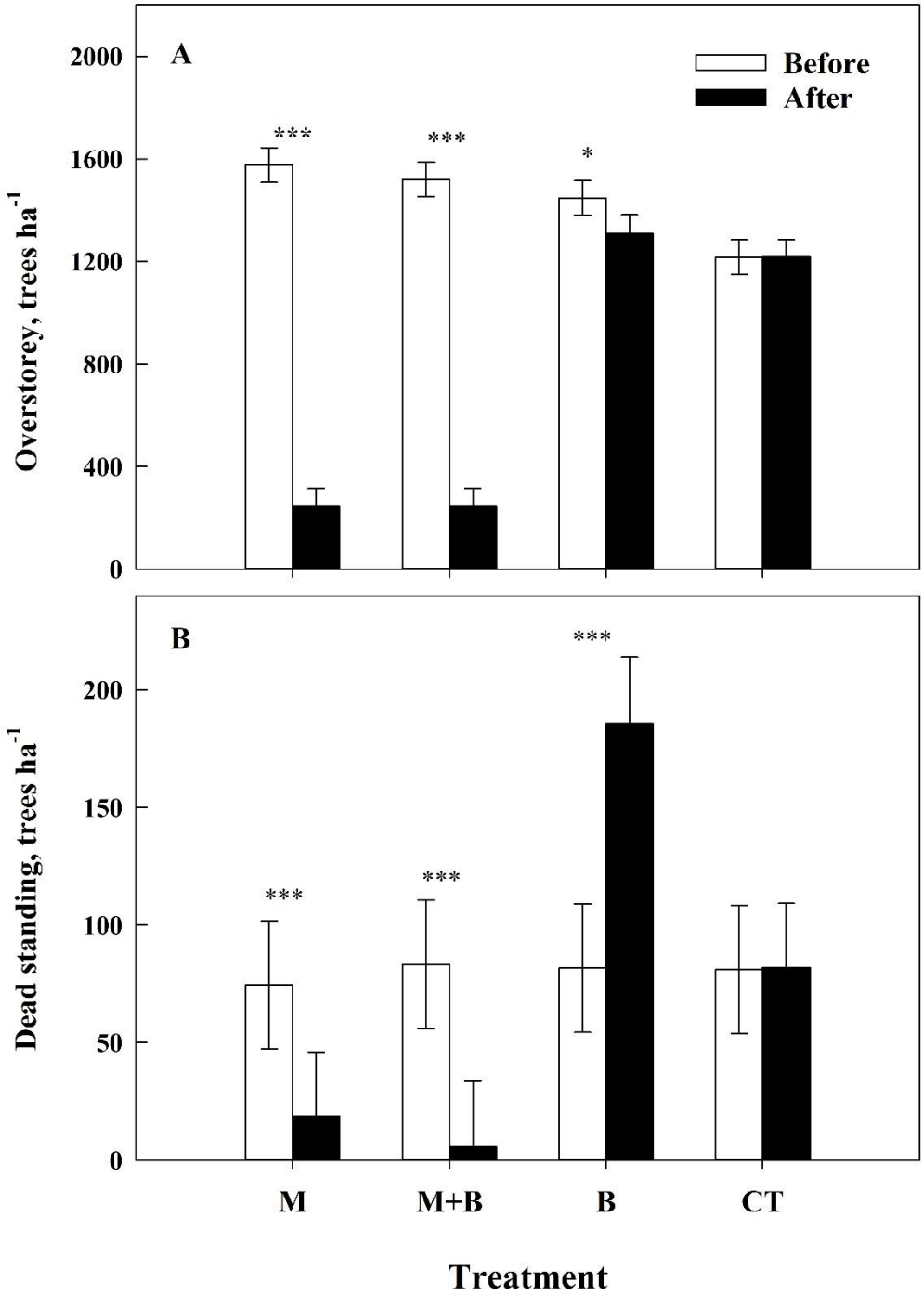

Figure 3. A) Number of live overstorey and, B) dead standing trees before (open bars) and after (grey bars) treatments, where: M – mechanical, M+B – mechanical + burn, B – burn, CT – control. Effect of treatment is represented by the significance level *** (P<0.001), * (P<0.05). Values are predicted means and error bars are standard error of the mean.

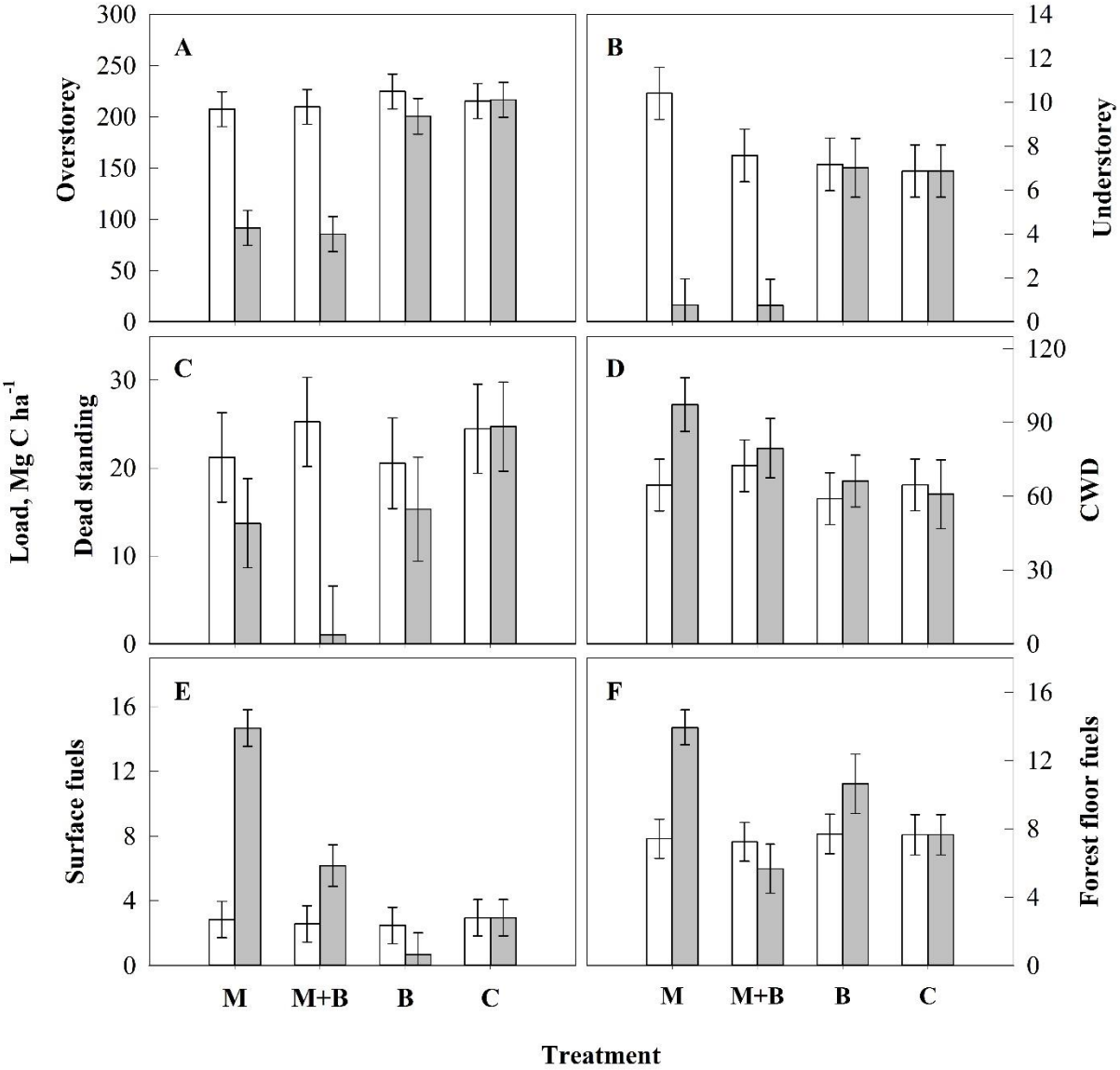

Figure 4. Forest carbon pools before (open bar) and after (grey bar) treatments, where: M – Mechanical thinning; M+B – Mechanical thinning and burn, B – Burn, and CT – Control. Effect of treatment is represented by the significance level *** (P<0.001), ** (P<0.01) and * (P<0.05). Values are predicted means and error bars are standard error of the mean.

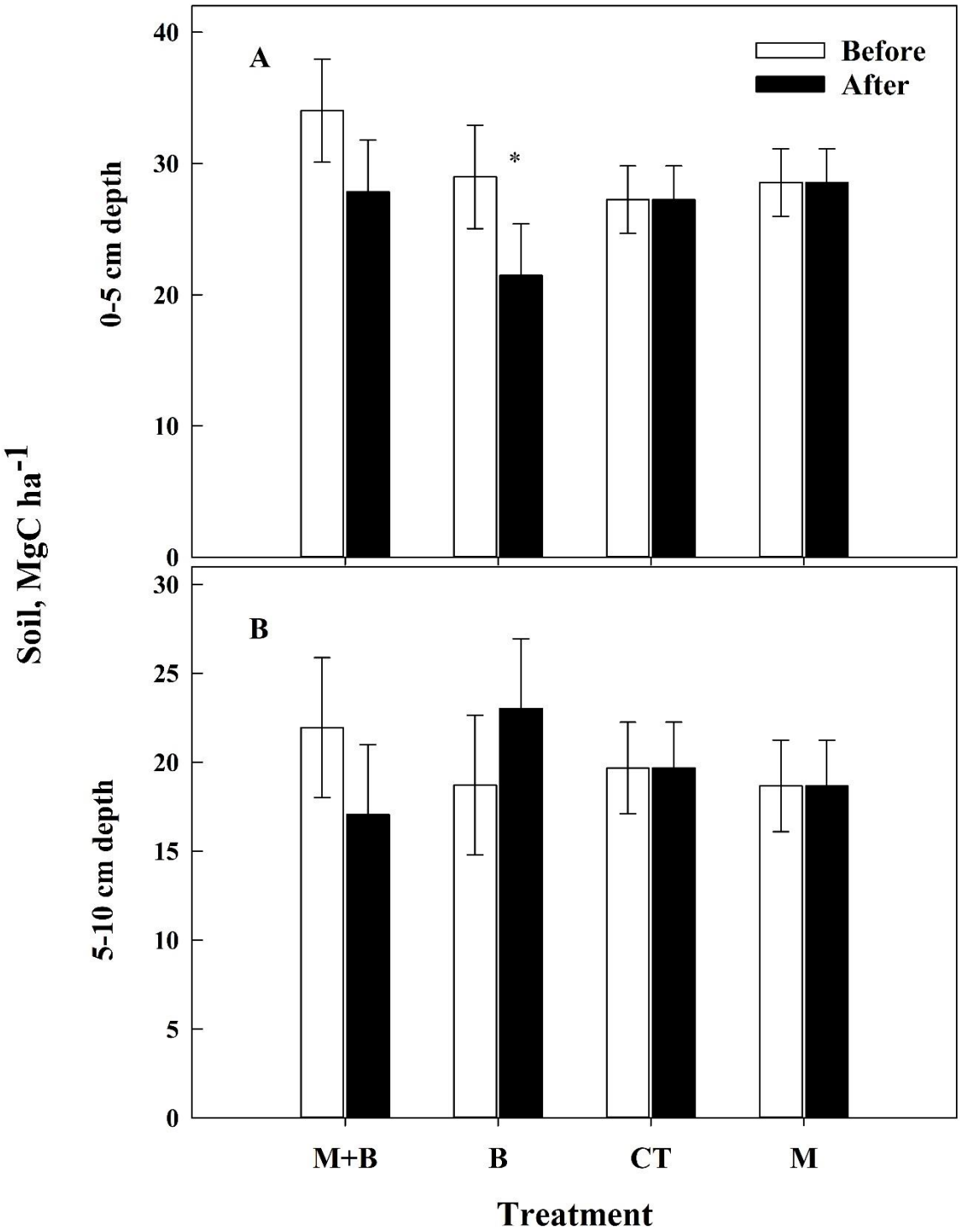

Figure 5. Soil carbon in A) 0-5 cm depth and B) 5-10 cm depth before (open bars) and after (grey bars) treatment. Where: M – Mechanical thinning; M+B – Mechanical thinning and burn, B – Burn, and CT – Control. * Effect of treatment was marginally significant (P=0.06). Values are predicted means and error bars are standard error of the mean.

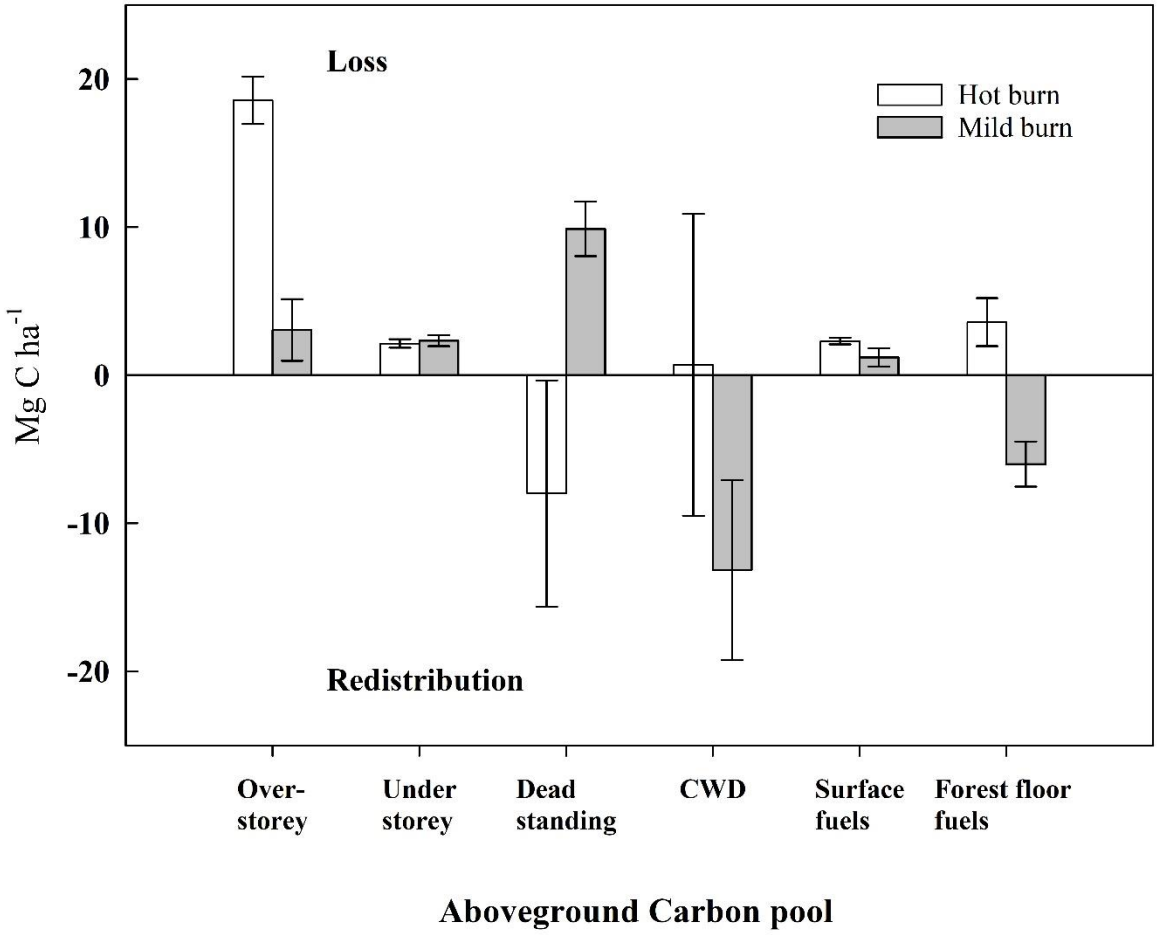

Figure 6. Carbon loss and redistribution in the Hot Burn and Mild Burn replicates of the Burn treatment. Values are means and error bars represent standard error of the mean.

Table 1. Inventory characteristics of study sites prior to application of mechanical thinning and burning treatments.

Parameter	Treatment			
	M	M+B	B	CT
Overstorey trees (Diameter at Breast Height, DBH) ≥10cm				
Dominant species,	(%)			
Eucalyptus sieberi	72	81	89	81
E. obliqua	26	17	8	15
Basal Area, m^2 ha^{-1}	57.4±1.3	55.9±1.0	57.9±1.5	55.8±1.5
Mean Height, m	22.3±0.1	22.4±0.1	22.9±0.2	23.2±0.2
Mean Diameter, cm	19.3±0.1	19.6±0.1	20.6±0.3	21.7±0.3
Small trees (Diameter at Breast Height, DBH) <10 cm				
Basal Area, m^2 ha^{-1}	6.60±0.45	4.91±0.41	4.58±0.41	4.53±0.38
Mean Diameter, cm	5.58±0.25	5.62±0.24	5.14±0.25	5.32±0.25
Soil, Mg C ha^{-1}				
Soil (0-10 cm)	47.2±2.41	51.2±4.50	46.2±4.52	46.9±2.57

Where: M – mechanical, M+B – mechanical + burn, B – burn, CT – control. Values are mean, ± is the standard error of mean, n = 60.

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