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Understanding Post-Fire Fuel Dynamics Using Burnt Permanent Forest Plots

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Cover: McKenzie and Lamb Range Ausplots in Tasmania before and after the fires. Photos: James Furlaud and Elinor Ebsworth.

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BACKGROUND

The Terrestrial Ecosystem Research Network (TERN) Ausplot Forests network is a long-term ecological monitoring network of 48 1-hectare plots in mature, tall, wet eucalypt forest. It was established between 2012 and 2015 with the goal of setting up a network of permanent forest plots on a continental scale across a large climactic gradient.[1] The climates in which these plots are located ranges from that of the cool temperate forests of Tasmania to the warm tropics of far north Queensland. The original objective was to set up the first Australia-wide network of plots in highly productive forests to monitor the effect of climate change on carbon stocks.[2] However, consistent with the overarching goal of TERN, these plots were also intended to contribute to a continental-scale infrastructure for scientific study. In keeping with this concept, researchers from the University of Tasmania visited all 48 plots in the summer of 2014-15 to measure the fuel loads in an attempt to understand fuel dynamics across a macro-ecological gradient.

Between October 2014 and January 2017, low-severity fires burnt four of the plots: two in North Queensland, one in northern Tasmania, and one in southwest Western Australia (figure 1). This provided an opportunity to measure the reduction in fuel loads caused by a low severity burn, and to get a baseline, post-fire measurement of fuel loads in wet eucalypt forests. The four plots that burned are outlined in table 1. The weather conditions during these fires, as taken from Bureau of Meteorology (BOM) forecast grids, are outlined in table 2.

The Tasmanian site (McKenzie) burnt in the Lake McKenzie Fire, part of the Mersey Forest Fire Complex, which burnt 25,723 ha between 15 January and 28 February 2016.[3] Though the fire garnered international headlines for its destruction of fire-intolerant ecosystems such as cushion plant, pencil pine, and king-billy pine,[4] the majority of the fire burned in wet and dry eucalypt forest (figure 2).

The plot is in a high-elevation *Eucalyptus delegatensis* forest characterised by moderate fire weather and a dense *Dicksonia antarctica* understorey. According to data from the Tasmania Fire Service, the plot likely burned on 24 January 2016. According to forecast grid data, the fire weather at the site on 24 of January was surprisingly mild, given the scale of the fire, with a maximum

Plot Name	State	Bioregion	Tenure	Lat/Long	Dominant Species	Original Measure-ment Date	Fire Type	Date of Fire	Re-measure-ment Date
McKenzie	TAS	TAS North Slopes	TFA Future Reserve	146.2593 -41.6303	*E. delegatensis*	3/3/2015	Wildfire	24/1/2016	15/11/2016
Lamb Range	QLD	Wet Tropics	Danbulla NP	145.4644 -17.4158	*E. grandis*	18/10/2014	Planned Burn	28/10/2014	4/11/2016
Herberton	QLD	Wet Tropics	Herberton Ranges NP	145.5609 -17.1107	*E. grandis*	23/10/2014	Planned Burn	13/8/2015	6/11/2016
Sutton	WA	Warren	Greater Dordagup NP	116.2498 -34.4488	*E. diversicolor*	25/1/2015	Planned Burn	20/1/2017	15/11/2017

TABLE 1: SUMMARY INFORMATION OF THE THREE TERN AUSPLOTS THAT BURNED BETWEEN OCTOBER 2014 AND JANUARY 2016, AND WHICH ARE THE FOCUS OF THIS STUDY. DATES OF THE FIRES AND FUELS MEASUREMENTS ARE ALSO INCLUDEED

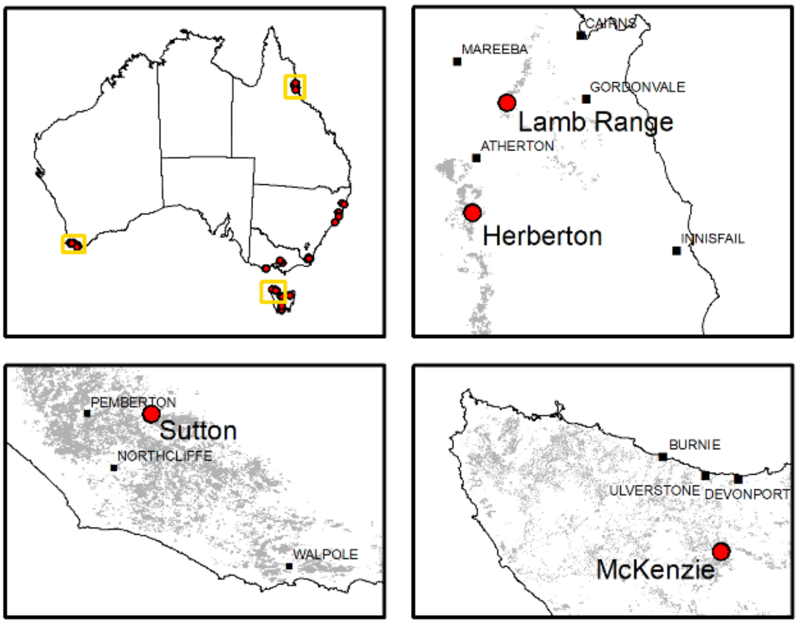


FIGURE 1: MAPS SHOWING: (A) THE LOCATION OF ALL AUSPLOTS (SMALL RED DOTS) AND THE REGIONS IN WHICH THE BURNT PLOTS ARE LOCATED (YELLOW RECTANGLES), AND THE LOCATION OF THE FOUR BURNT AUSPLOTS IN THEIR RESPECTIVE REGIONS, (B) NORTH QUEENSLAND, (C) SOUTHWEST WESTERN AUSTRALIA, AND (C) CENTRAL TASMANIA. NAMES OF THE BURNT AUSL=PLOTS ARE GIVEN IN LARGE TYPE. THE GREY SHADED AREAS REPRESENT THE EXTENT OF TALL WET EUCALYPT FOREST IN THE REGION.

Forest Fire Danger Index (FFDI) of 10 (Table 2). The nearest weather station (~45 km away) indicate that the fire weather had improved substantially in the three days leading up to 24 January.[5] Indeed, when the fire swept through the McKenzie plot, it did so at a much lower severity than in the surrounding areas, with almost no overstorey mortality occurring.

The two sites in Queensland (Lamb Range and Herberton) were subject to planned burns in 2014 and 2015. Given the remote nature of these planned burns, not as much information is available. The burn at Lamb Range was ignited via an aerial incendiary run and was of moderate intensity (in the context of planned burns). Its primary goal was to prevent rainforest encroachment, which it did quite successfully.[6] Meanwhile Herberton was burned under mild conditions and produced a low intensity fire.[6]

The planned burn in Western Australia was initiated on 20 January 2017, it was considered by managers to be quite successful with complete mortality in the elevated fuels layer, and little to no scorch of the canopy.[7] It also was performed on a day with quite mild fire weather, with a forecast FFDI of 11.

These fires presented us with an excellent opportunity to obtain fuel load measurements both directly before and after low severity fires. Not only would such

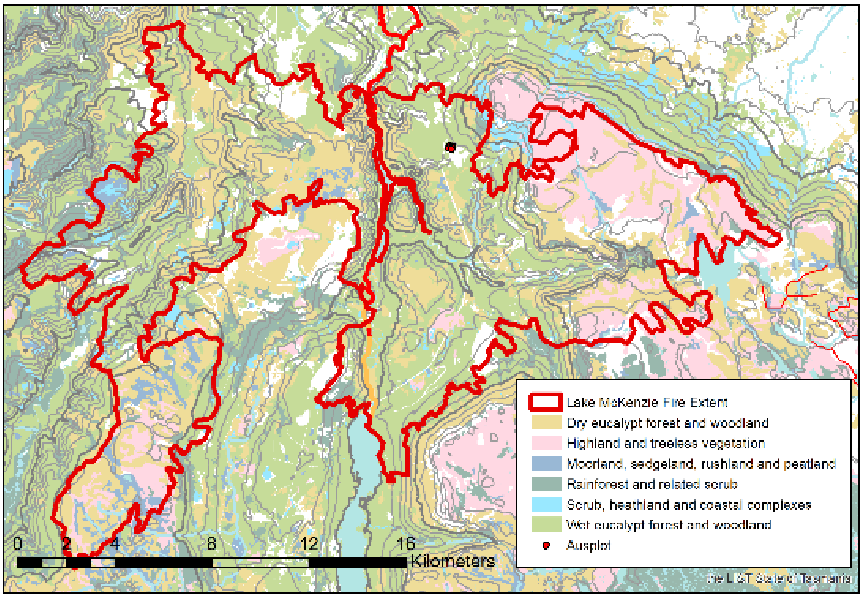


FIGURE 2: MAP SHOWING EXTENT OF THE LAKE MCKENZIE FIRE, THE LOCATION OF THE MCKENZIE AUSPLOT, AND THE DISTRIBUTION OF THE MAJOR NATIVE VEGETATION TYPES IN THE REGION. DATA SOURCES: TASMANIA FIRE SERVICE[3] AND TASVEG 3.0[7]

Plot Name	**Fire Type**	**Date of Fire**	**Temperature (°C)**	**Relative Humidity (%)**	**Wind Speed (km/h)**	**Drought Factor**	**FFDI**
McKenzie	Wildfire	24/1/2016	22.7	37.1	16.92	8.9	10
Lamb Range	Planned Burn	28/10/2014	28.4	28	21.24	10	21
Herberton	Planned Burn	13/8/2015	22	30	5.76	10	13
Sutton	Planned Burn	20/1/2017	26.4	36.9	11.52	9.8	11

TABLE 2: SUMMARY OF WEATHER CONDITIONS FOR THE FOUR FIRES AT 3PM (LOCAL TIME) ON THE DAY OF THE FIRE. TEMPERATURE (°C), RELATIVE HUMIDITY (%), WIND SPEED (KM/H), DORUGHT FACTOR, AND MCARTHUR'S FOREST FIRE DANGER INDEX ARE GIVEN.

measurements provide an estimate of how much fuel is consumed in planned burns, but such fuels data could be used to input into fire behaviour model simulations and quantify a probabilistic risk reduction associated with the planned burns.

Additionally, it will provide baseline fuel loads directly after a fire. This is valuable as fire behaviour models predict fuel accumulation as a function of time since previous fire, therefore knowing the starting point for fuel accumulation is incredibly important.

OBJECTIVE

The main goal of this study is to obtain empirical measurements of fuel loads within the first year after a fire to complement the measurements of fuel loads taken directly before the fires. This will not only allow us to precisely quantify the fuel loads consumed by these relatively low-severity fires, but it will also give us a baseline measurement of fuel loads. We can use this baseline to anchor measurements of fuel accumulation in mature wet eucalypt forests that are part of related TERN and BNHCRC studies attempting to measure both the effects of climate and stand age on fuel accumulation in wet forests.

CURRENT STATE OF KNOWLEDGE

As the rate of spread and intensity of a fire is a function of fuels, fire weather and topography,[8] and as only the latter can be physically manipulated, the effect of fire on fuel loads is extremely important to understand. Planned burning is the most commonly employed fuel reduction technique in Australia. The underlying concept is that burning off fuel loads across a landscape leads to an increased encounter rate with low fuel load areas.[7] While reducing fuel ages has been shown to reduce both the extent and incidence of unplanned fires,[9,10,11] the effect of low severity fires on actual fuel loads has not been explicitly quantified. While the period of effectiveness of a planned burn has been generally reported to be 5-6 years,[8,12] these studies have looked at the empirical probability or size of unplanned fires as a function of fuel age, no studies that we could find in Australia measured fuel loads directly after a low-severity fire.

RELATED PROJECTS

This study is will add valuable data to a BNHCRC funded PhD project at the University of Tasmania with the Tasmania Fire Service serving as the lead end-user. The project is attempting to re-calibrate the fuel accumulation curves for wet sclerophyll forests in Tasmania by measuring fuel loads in forests with a wide range of fuel ages. To add a third dimension to these fuel accumulation curves, we plan to use the data from the TERN Ausplot fuel surveys to see how different climates affect forest structure and fuel accumulation, and potentially calibrate our Tasmanian fuel curves for different climate change scenarios outside of the current Tasmanian climactic range. Additionally, this study will add a valuable section to a forthcoming peer-reviewed paper on the variation of fire regimes in wet eucalypt forests across the continent. We will use the data to investigate how the effectiveness of planned burning varies under different fire regimes.

Lastly, the long-term goal of this project is to run large-scale fire behaviour model simulations investigating fuel treatments and risk reduction in Tasmania's wet forests. As we will have quantified the actual fuel reduction associated with low severity burns, which are a significant part of the Tasmanian wet forest fire regime, this could allow us to calibrate the model to make the model simulations more realistic.

RESEARCH QUESTIONS

This study plans to focus on three major research questions:

- What is the effect of low-severity fires on fuel loads in tall wet eucalypt forests?
- What is the risk reduction associated with planned burning and low-severity fires?
- How well do these time-zero measurements fit into fuel accumulation curves that have been adjusted for climate change using data from the original TERN fuel surveys

METHODS

We originally established the TERN Ausplot forest monitoring plots between September 2012 and January 2015, creating detailed tree maps. For these maps, we recorded the diameter at breast height (DBH), height, height to crown base (HCB), and exact location of each tree. We measured the fuel loads in all the plots in the summer of 2014-15. We re-measured the plots that had burnt in November 2016 and November 2017. The methodology for the fuel surveys of these plots was derived from NASA-funded fuel surveys.[13]

TERN AUSPLOTS FORESTS FUEL SURVEYS

From October 2014 – February 2016, we performed fuel load surveys along four 28.3 m transects in each of the Forest Ausplots (figure 4). We measured the surface fine fuel load and near-surface biomass in tonnes per hectare (t/ha). We measured the input and output rates for surface fine fuels using litterfall traps and decomposition bags. We also measured surface woody fuels and the depth of the litter and grass, along with the height and density of ferns and shrubs in the elevated fuel layer. Lastly we measured the temperature and humidity in the understorey over the course of a year using iButtons. A detailed account of all the fuel survey techniques for the Ausplots Forests Fuels Survey can be found in the field manual.[14] Not all the data from these methods is presented in the results, but all the data will be available on the AEKOS TERN Data Portal.[15]

Surface and Near-surface Fuels

Quadrats for fine fuels, herbs, and vines

We set up 1x1 m quadrats between the 7-8m and 21-22m marks along the transect tape. Along the inside edge of each quadrat we measured the litter depth and grass height at 10cm intervals between 7.0 and 7.8 m, and 21.2 and 22.0 m on the transect tape. We then ocularly estimated percent cover for fine fuels, live and dead herbs, shrubs, vines, and moss within each quadrat. We followed by collecting all the attached vines, live herbs (defined as all non-woody vegetative plants, excluding ferns), live grasses, and lastly fine fuels (all detached dead material, including twigs <6mm in diameter) from each quadrat. We measured the fresh weight of all collected materials on site and returned to the lab a subsample of at least 350g of each fuel category from each quadrat. At the lab, we dried these subsamples to a constant weight at 70°C, and weighed them to obtain a dry weight to fresh weight ratio. We then used these ratios to convert the fresh weight of the rest of the sample to dry weights. Lastly we measured the depth of the topmost organic layer in the soil.

Litterfall Traps and Decomposition Bags

To measure the input and output rates of fine fuel, we set up a litterfall trap at the end of each transect and decomposition bags near the beginning of the first transect. The litterfall traps were constructed of 32mm diameter PVC pipe


(A) (B)

FIGURE 3: PHOTOS OF ASSEMBLED LITTERFALL TRAP (A) AND DECOMPOSTION BAG (B). EACH WAS LEFT AT THE SITE FOR ROUGHLY ONE YEAR TO MEASURE ANNUAL INPUT AND OUTPUT RATES OF FINE FUELS.[2]

and shade cloth. We assembled the pipes to create a 0.75m x 0.75m square to cover an area of 0.56m^2, the square was elevated 0.47m above the ground and covered in shadecloth to catch falling litter (Figure 3.a). The decomposition bags were 20cm x 20cm, constructed of 152 μm mesh, sewn together on three sides. We filled 15 of the bags with roughly 10g of oven-dried litter from the quadrats, and six of the bags with a cotton calico square. We slipped an aluminium tree tag in each of the bags to identify it and recorded the precise weight of the bag. We then pinned all 21 bags into the ground near the beginning of the first transect using weed mat pegs (Figure 3.b). The bags were left at the site for roughly one year to estimate an annual decomposition rate. We also set up iButtons at the end of three transects to measure the temperature and humidity in the understorey.

Downed Woody Fuels

We measured downed woody fuels along each transect to estimate the biomass of this fuel type. Downed woody fuels were defined as any detached (not rooted in the ground) woody material. We divided downed woody fuels into 3 categories, based on 1, 10, and 100 hour moisture time-lag classes[16,17]: (a) 0.6-2.5cm diameter, (b) 2.5-7.6cm diameter, and (c) >7.6cm diameter. For category c, we measured the diameter of every log or fragment that intercepted the transect tape in this size class. The diameter was measured perpendicularly to the direction of the log at the point of intersection. For categories a and b, we counted the number of woody intersects between the 6-8m and 20-22m marks on the transect tape, and between the 5-7m and 19-23m marks, respectively. A full diagram of the locations of the quadrats and woody fuel counts along the transect tape is presented in figure 4. We then used the standard technique for converting the diameter of downed logs into t/ha, assuming a relative density of 0.4.[18,19]

Surface and Near-surface Fuels

Live Plant Measurements

To measure live plants in the elevated fuel layer (hereafter referred to as “shrubs”), we split the transect tape into four 7m long subsections. In each of these subsections we measured the 5 shrubs that were perpendicularly closest

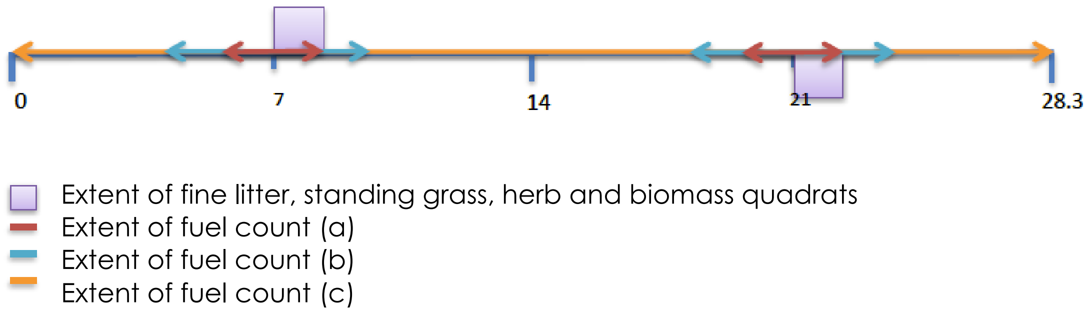


FIGURE 4: EXTENT OF WOODY FUEL COUNTS AND FINE FUEL QUADRTATS[2]

to the tape. We considered any plant that had a stem that “snapped” (namely woody plants and ferns), and were less than 10cm in DBH to be a shrub. We also included tree ferns in this category. In each subsection, we recorded the life form of each shrub, and measured the height of each shrub and the DBH of each shrub greater than 1.3m in height. We also measured the length and width of a rectangle bounding the group of five shrubs so we could estimate density (Figure 5). These measurements gave us estimates of the density and height of the elevated fuels layer. We then developed allometric equations using the work of Paul *et al.* (2016) and the data of Falster *et al.* (2015), that predicted biomass of fine fuels based on DBH or height, in order to obtain a tonnes per hectare (t/ha) estimate.[20,21]

REMEASUREMENT OF BURNT AUSPLOTS

In November of 2016 and 2017, we returned to the four Ausplots that had burnt after the initial fuel surveys. For the most part, we followed the methodology of the original surveys, however we made some notable changes which are outlined below.

Surface and Near-Surface Fuels

To save time during the re-measurement, we collected the small woody fuels (0.6-2.5cm diameter) in the fine fuels quadrat rather than counting them on the transect in subsection (a)(figure 4), and we refer to these fuels as course fuels hereafter. We also were able to transport all the collected material to the lab for drying, so we did not have to take subsamples in the field. However, we

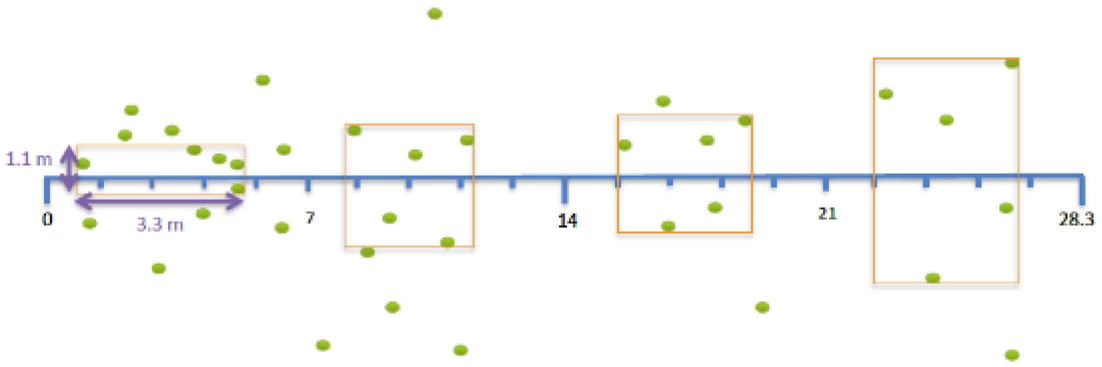


FIGURE 5: DIAGRAM OF CHOICE OF SHRUBS AND MEASUREMENT OF SURROUNDING RECTANGLE.[2]

collected more grass at the Herberton site than could fit in the drying oven, so we had to dry a subsample of grass in the lab, and estimate the remaining dry weight in the same manner as before. We dried a subsample from each quadrat.

FIGURE 6: LITTERFALL TRAP AND DECOMPOSITION BAG SET-UP FOR TASMANIAN REMEASUREMENTS

Additionally, we did not set up litterfall traps, decomposition bags, or iButtons in the Queensland sites, as this equipment had been destroyed in the fires prior to being collected, so we had no pre-fire data to which we could compare it. We also could not set up litterfall traps, decomposition bags, or iButtons in the Western Australian site due to logistical issues. For the decomposition bags in Tasmania, we split them up into 5 groups of four. The first group was composed only of bags containing calico strips. We placed this group in the original decomposition bag location near plot centre. This allowed us to compare baseline rate pre- and post-fire. The four other groups comprised one bag containing calico strips, and three bags containing roughly 25g of dried litter each from similar sites in Southern Tasmania. Each of these groups of bags was placed roughly 1m away from a litterfall trap (Figure 4). This allowed us to more directly couple litterfall rates and decomposition rates.

Elevated Fuels

We made all the same measurements in the elevated fuels as in the original fuel surveys. We also took a number of additional measurements. To be able to more accurately estimate standing biomass, we measured the basal diameters of all shrubs <1.3m in height. When shrubs had multiple stems we measured the diameter of the largest stem, then counted the number of additional stems and estimated their average diameter. We grouped all shrubs into one of four growth form categories: tree, shrub, fern, or tree fern. Lastly we repeated the live shrub methodology for all standing dead shrubs.

Fire Severity

To measure severity of the fires, we measured the DBH of each tree (considered any plant with a DBH >10cm) within 15m or 18m of each transect (depending on the number of trees). This allowed us to look at the reduction in bark resulting from the fires. We also measured the height of the highest and lowest point of the fire scar on each using a vertex hypsometer.

FINDINGS

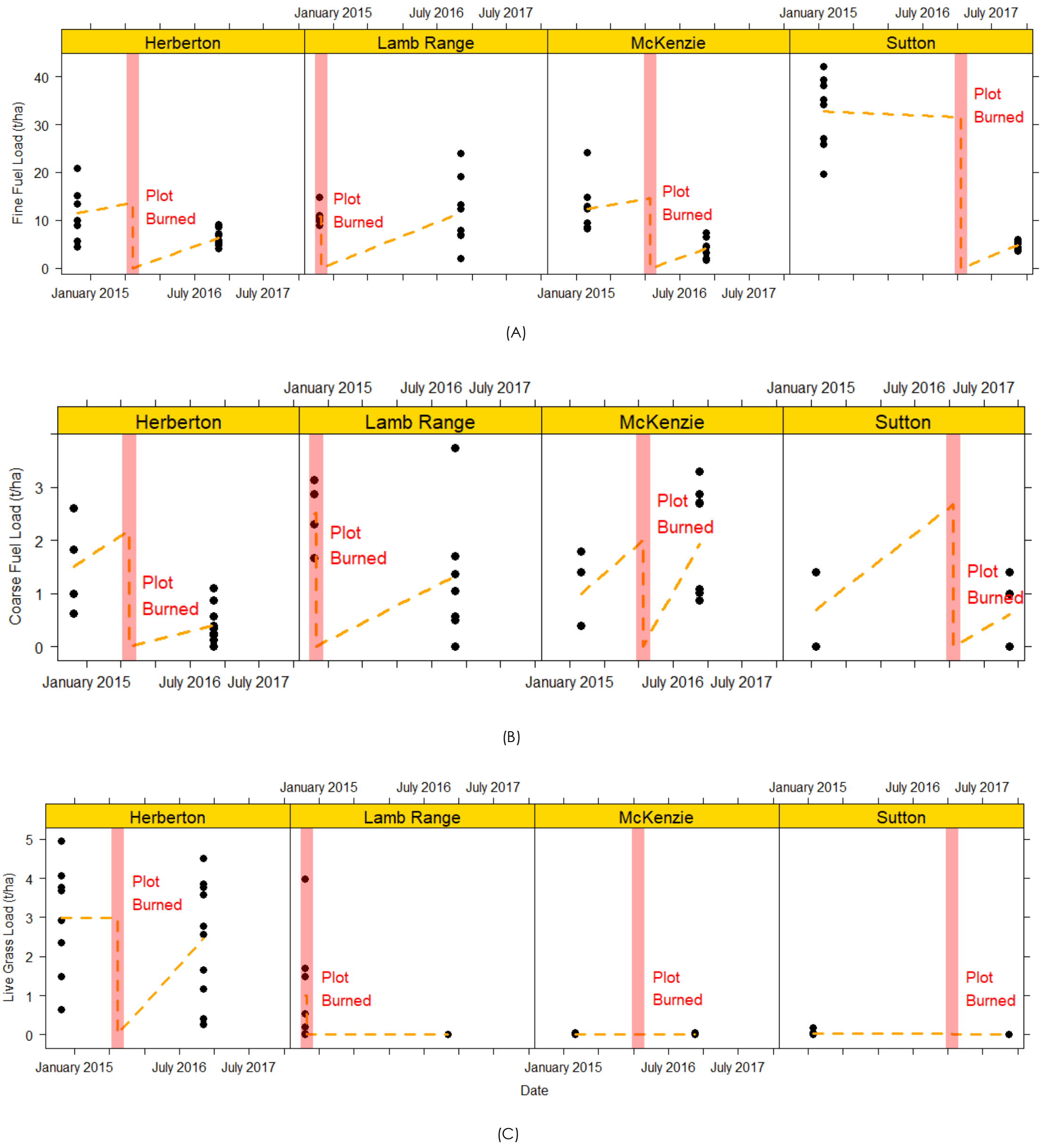
Preliminarily, this study has revealed that the effect of planned burning on fuel loads is highly dependent on region, and varies among the fuel layers. It appears that planned burning is quite effective at reducing fuel loads and fire danger in regions characterised by large fuel loads and bad fire weather. However, surface fuel loads can recover quite quickly after a low severity burn in regions where they were not particularly high to begin with. Our most consistent finding was a significant reduction in live, elevated fine fuel loads in every site. We did not find any interesting patterns in the height of tree scorch, however, more detailed analysis is required to fully understand the data on elevated fuels and fire severity. Our results suggest that the effectiveness of planned burning in reducing fire hazard varies based on fuel structure and climate. This suggests a need for careful design of planned burning regimes.

SURFACE AND NEAR-SURFACE FUELS

Fine and Coarse Fuels

Among the most interesting results in this study is that the surface fine fuel loads seem to have returned to their pre-burn levels within two years at Lamb Range, and seem to be on a similar trajectory in Herberton and McKenzie. Meanwhile, in Sutton, where fuel loads were extremely high prior to the fire, planned burning appears to have substantially reduced the fine fuel load (figure 7a). Given the primary importance of fine fuels in driving fire behaviour, this is potentially an important result regarding the effectiveness of planned burning in reducing fire danger in different climactic regions of wet eucalypt forests.

The trend among grasses and coarse fuels is less consistent (figures 7b, 7c). The grass fuel loads seem to have quickly regrown in Herberton, where the site was being colonised by the highly flammable *Imperata cylindrica*[22], but in Lamb Range the fire seems to have successfully eliminated grasses. The coarse fuel loads seem to rapidly re-accumulate after the burn. This may be the result large input of burnt dead shrubs and branches directly after the fire. That these latter two fuel types can re-accumulate so rapidly also suggests a potential for fire risk to return to pre-burn level relatively quickly, especially in areas with moderate fuel loads to begin with.



(A)

(B)

(C)

FIGURE 7: TIMELINE OF SURFACE FUEL LOADS (IN TONNES PER HECTARE) AT THE THREE SITES. (A) DEPICTS FINE FUELS, (B) COARSE WOODY FUELS (0.6-2.5 CM DIAMETER, 1 HOUR DRYING CLASS) AND (C) LIVE GRASS. THE BLACK DOTS REPRESENT INDIVIDUAL QUADRATS, AND THE ORANGE DOTTEDD LINE REPRTESENTS THE ESTIMATED FUEL ACCUMULATION PATTERN. FUEL ACCUMULATION WAS INFERRED FROM PREVIOUSLY MEASURED RATES (SEE METHODS) AND ASSUMED COMPLETE CONSUMPTION THE THREE FUEL TYPES DURING THE BURN.

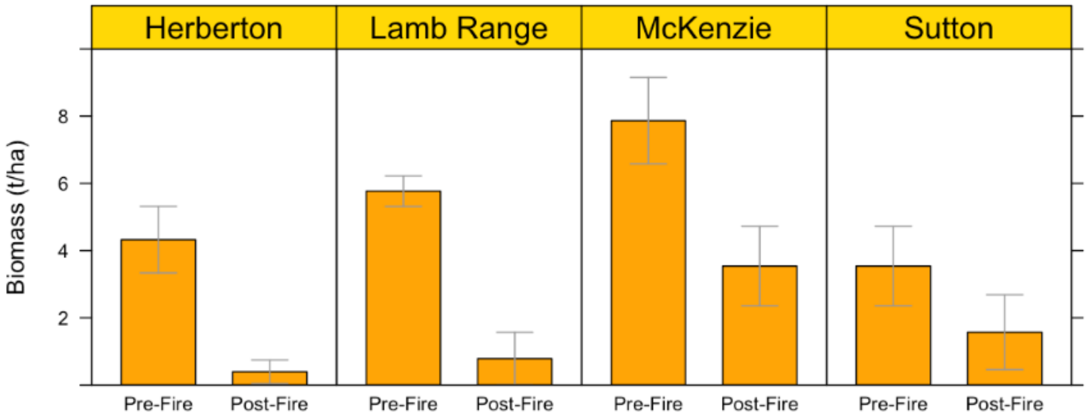
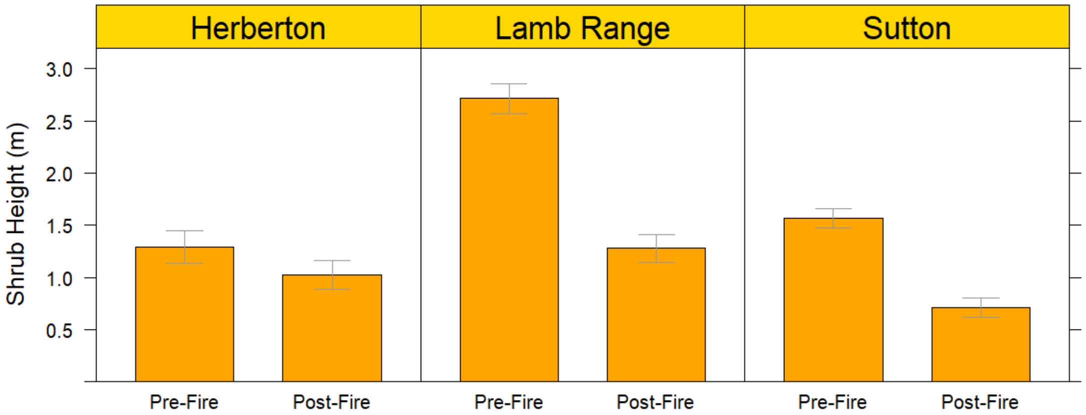
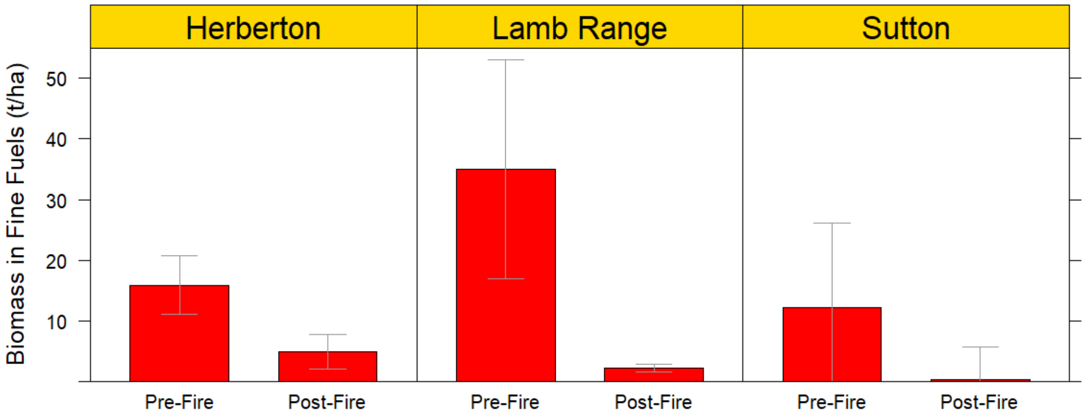


FIGURE 8: BIOMASS IN TONNES PER HECTARE OF 10 HOUR DRYING CLASS (2.5-76 CM DIAMETER) COARSE WOOY DEBRIS, BOTH BEFORE AND AFTER THE FIRE. GRAY ERROR BARS REPRESENT ONE STANDARD ERROR.



(A)



(B)

FIGURE 9: THE MEAN (A) SHRUB HEIGHT AND (B) BIOMASS OF FINE FUELS IN THE ELEVATED LAYER ALONG THE FUELS TRANSECTS AT EACH SITE, BOTH BEFORE AND AFTER THE FIRE. GRAY ERROR BARS REPRESENT ONE STANDARD ERROR.

Downed Woody Debris

In terms of the downed woody debris, there seems to be a large and likely significant reduction in the biomass of 10-hour drying fuels (figure 8). Such a result may suggest that an advantage of planned burning is a reduction in the mid-sized 10-hour drying fuels, which burn more sustainably than the fine fuels, and can result in longer residence time of the fire. However, once again these empirical fuel loads need to be further analysed with models to fully understand their effect on fire risk.

ELEVATED FUELS

Perhaps the most consistent result across all sites was the substantial reduction in live elevated fuel loads and height after the fires (Figure 9). It should be noted that the post-fire estimate does not include the standing dead shrubs, as we have not yet developed an allometric equation to predict biomass of dead shrubs. As a result, the actual post-fire biomass of fine fuels in the elevated layer is likely slightly higher, but still almost certainly less than pre-fire fuel loads. We did not include McKenzie in this analysis because we currently have not

(A) (B)

FIGURE 10: THE ELEVATED FUEL LAYER IN MCKENZIE CONSISTED PRIMARILY OF *DICKSONIA ANTARCTICA* BOTH (A) BEFORE AND (B)

developed accurate allometric equations for small tree ferns, which represent the majority of plants present in the elevated layer at that site after the fire (figure 10b). However, visual assessments indicate the elevated fuel layer was thick with live and dead fronds of *Dicksonia antarctica* prior to the fire, all of which were consumed in the fire (figure 10).

THE EFFECT OF PLANNED BURNING ON FIRE BEHAVIOUR

To investigate the effect of planned burning on fire behaviour we simulated flame height using McArthur's MK5 equations for fire behaviour.[23] For inputs we used our empirical measurement of the surface and elevated fuel loads and FFDI calculated from historical climate data from the Scientific Information for Land Owners (SILO) patched-point meteorological dataset.[24] We calculated flame height using 80th percentile and above FFDI measurements (meant to roughly represent fire season weather) from the SILO stations between 1960 and 2012 and our surface and elevated fuel biomass estimates. This gave a distribution of potential flame heights for fires in both the surface and elevated fuel layers in each of the four sites both before and after the fires. We then overlayed these boxplots over the distribution of heights to the crown base of the sites' overstories to visualise the probability of canopy ignition (figure 10).

From this graph, it appears that the effect of planned burning on surface fires is quite region-specific. In Mckenzie, which is a high-elevation site, the fires seem to substantially reduce flame height, but the low FFDI of the region means that the probability of ground fires reaching the crown was quite low both before and after the fire. However, it should be noted that the dominant overstorey species in these forests in *Eucalyptus delegatensis*, which can carry fires up it's stringy bark into the canopy, so the probability of crown scorch is likely higher than this graph would indicate. Meanwhile, in Sutton, which is a Western Australian forest characterised by high fuel loads and bad fire weather, planned burning seems to have significantly reduced the probability of a crown fire. The two Queensland sites seem to have a relatively high probability of crown ignition, regardless of planned burning, due to bad fire weather and a low base of the canopy. However, we know that both these sites burned at a low severity (without crown scorch) at FFDI's of 21 and 13, suggesting that McArthur's equation is likely over predicting flame heights. These results suggest that the effectiveness of planned burning is quite context-dependant and needs to be carefully planned.

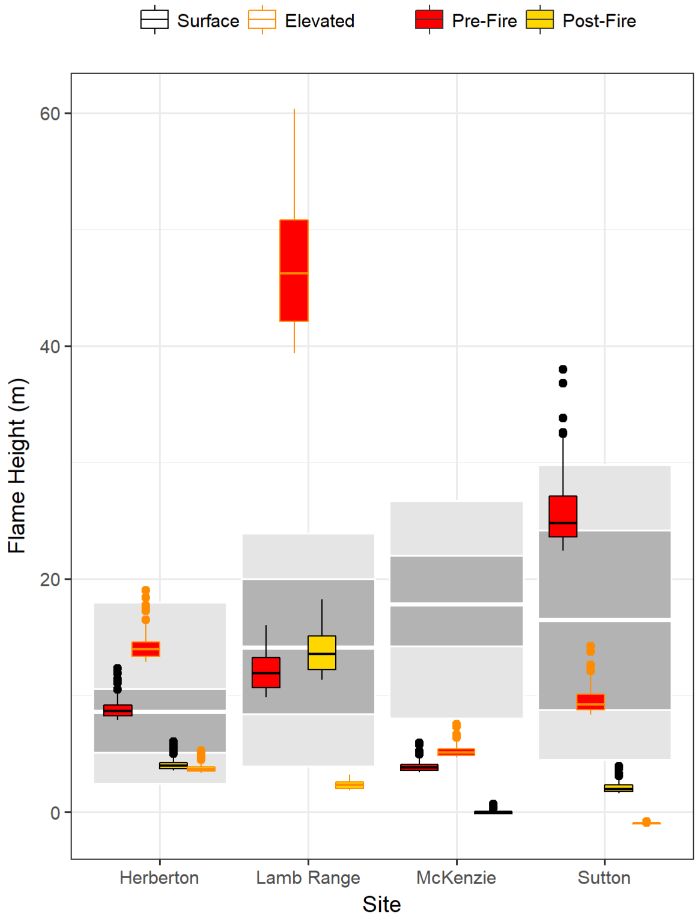


FIGURE 11: DISTRIBUTION OF SIMULATED FLAME HEIGHTS BOTH BEFORE AND AFTER THE FIRES IN EACH SITE USING DATA FROM BOTH THE SURFACE AND ELEVATED FUEL LOADS. FLAME HEIGHTS WERE CALCULATED FROM MCARTHUR'S MK5 EQUATIONS USING EMPIRICALLY MEASURED FUEL LOADS AND FFDI DATA FROM SILO STATIONS FROM 1960-2012. DARK GREY BOXES REPRESENT 25TH-75TH PERCENTILE HEIGHTS TO CROWN BASE IN EACH SITE. LIGHT GREY BOXES REPRESTENT 5TH TO 95TH PERCENTILE HEIGHTS TO CROWN BASE. WHITE LINE REPRESENTS THE MEAN HEIGHT TO CROWN BASE

Meanwhile the extremely high simulated flame heights using the data from the elevated fuels are an indication of the unsuitability of McArthur's fire behaviour for the elevated fuels in wet eucalypt forest. For instance, according to McArthur's equations, the planned burn in Lamb Range should have had flame heights higher than 40m, based on the elevated fuel loads, but the scar heights on the overstorey trees were only a few metres high. The McArthur model was built using observations of fire behaviour in the surface fuels of dry eucalypt forests in New South Wales.[23] Meanwhile the elevated fuel layer in wet eucalypt forests in composed of mostly live, moderately-flammable trees and ferns, which will be much less flammable than dead *Eucalyptus* leaves. This is an important observation, as the Phoenix model currently treats the elevated and fine fuels as one singular mass. These results underscore the need to develop fire behaviour models that can more-accurately predict fire behaviour in live sclerophyllous understories, and more generally in wet eucalypt forests as a whole.

FUTURE USE OF OUTCOMES

The next step is to use these data in actual fire behaviour models such as Phoenix or Spark to see how fires might behave before and after prescribed burning in an actual landscape. Before we do that we need to develop allometric equations to predict the biomass of dead shrubs so we can get a complete estimate of elevated fuel loads. We also need to calculate, as our second measure of severity, how much bark was consumed in these fires. In some cases, two years passed between when the overstorey trees were originally measured and when they were measured after the fires. As a result, we will need to use tree growth models to measure the reduction in expected tree growth associated with these burns.

With this more complete data on elevated fuels and severity, we can look at fine scale trends in how the elevated fuel load affected fire severity. This is an important question, given that the thick elevated fuel loads in wet forests result in them being considered untreatable in some regions.

Lastly, our data describing the fuel loads at a fuel age of essentially zero will give us valuable insights into our attempts to adjust fuel curves for future climactic changes. Because we have a large dataset describing the effect of climate on fuel accumulation rates in mature forests, this new data will give us a second point in time with which to anchor our adjusted fuel curves. These adjusted fuel curves could be extremely useful, as they could lead to risk-reduction simulations under future climate scenarios.

REFERENCES

1 Wood SW, Stephens H, Bowman DM. Ausplots Forest Monitoring Network: Plot Establishment Report. 2015.
2 Wood SW, Prior LD, Stephens HC, Bowman DM. Macroecology of Australian Tall Eucalypt Forests: Baseline Data from a Continental-Scale Permanent Plot Network. PLoS One 2015; 10: e0137811.
3 AFAC Independent Operational Review: A review of the management of the Tasmanian fires of January 2016. Australasian Fire and Emergency Service Authorities Council 2016.
4 Slezak M. Tasmanian bushfires 'worst crisis in decades' for world heritage forests. In: The Guardian Australia, 2016.
5 Liawenee, Tasmania: January 2016 Daily Weather Observations. Bureau of Meteorology; [cited 8 February 2016]; Available from: http://www.bom.gov.au/climate/dwo/201601/html/IDCJDW7027.201601.shtml.
6 Goetze K, Personal Communication, Queensland Parks and Wildlife Service 31 January 2017
7 McCaw L, Personal Communication, Western Australia Department of Parks and Wildlife, 13 November 2017
8 Fernandes PM, Botelho HS. A review of burning effectiveness in fire hazard reduction. International Journal of wildland fire 2003; 12: 117-28.
9 Boer MM, Sadler RJ, Wittkuhn RS, McCaw L, Grierson PF. Long-term impacts of prescribed burning on regional extent and incidence of wildfires—Evidence from 50 years of active fire management in SW Australian forests. Forest Ecology and Management 2009; 259: 132-42.
10 Price OF, Penman TD, Bradstock RA, Boer MM, Clarke H. Biogeographical variation in the potential effectiveness of prescribed fire in south-eastern Australia. Journal of Biogeography 2015; 42: 2234-45.
11 Bradstock RA, Cary GJ, Davies I, Lindenmayer DB, Price OF, Williams RJ. Wildfires, fuel treatment and risk mitigation in Australian eucalypt forests: insights from landscape-scale simulation. Journal of Environmental Management 2012; 105: 66-75.
12 Price OF, Bradstock RA. The effect of fuel age on the spread of fire in sclerophyll forest in the Sydney region of Australia. International Journal of Wildland Fire 2010; 19: 35-45.
13 Prior LD, Murphy BP, Williamson GJ, Cochrane MA, Jolly WM, Bowman DMJS. Does inherent flammability of grass and litter fuels contribute to continental patterns of landscape fire activity? Journal of Biogeography 2016: n/a-n/a.
14 Wood S, Stephens H, Foulkes J, Ebsworth E, Bowman D. Ausplots Forest Monitoring Network: Survey Protocols Manual. Terrestrial Ecosystem Research Network (TERN), 2014.
15 Terrestrial Ecosystem Research Network AEKOS Data Portal; [cited 9 March 2018]. Available from: http://aekos.org.au/index.html#/home
16 Brown JK. Handbook for inventorying downed woody material. 1974.
17 Fosberg MA. Drying rates of heartwood below fiber saturation. Forest Science 1970; 16: 57-63.
18 Marshall P, Davis G, Taylor S. Using Line Intersect Sampling for Coarse Woody Debris: Practitioners Questions Addressed. Naniamo, BC, Canada, Research Section, Coast Forest Region, BC Ministry of Forests, 2003. Extension Note EN-012.
19 Mackensen J, Bauhus J. The Decay Of Coarse Woody Debris. In: National Carbon Accounting System, Australian Greenhouse Office, 1999.
20 Paul KI, Roxburgh SH, Chave J, England JR, Zerihun A, Specht A, Lewis T, Bennett LT, Baker TG, Adams MA, Huxtable D. Testing the generality of above-ground biomass allometry across plant functional types at the continent scale. Global change biology. 2016 Jun 1;22(6):2106-24.
21 Falster DS, Markesteijn L, Poorter L, Sterck FJ, Anten NP. BAAD: a Biomass And Allometry Database for woody plants. Ecology. 2015;96(5):1445.
22 Pickford S, Suharti M, Wibowo A. A Note on Fuelbeds and Fire Behavior in Alang-Alang (*Imperata Cylindrica*). International Journal of Wildland Fire 1992; 2: 41-6.3.
23 Noble IR, Gill AM, Bary GA. McArthur's fire-danger meters expressed as equations. Austral Ecology. 1980 Jun 1;5(2):201-3.
24 Jeffrey SJ, Carter JO, Moodie KB, Beswick AR. Using spatial interpolation to construct a comprehensive archive of Australian climate data. Environmental Modelling & Software. 2001 Jun 1;16(4):309-30.