bushfire&natural HAZARDSCRC

bnhcrc.com.au

UNDERSTANDING POST-FIRE FUEL DYNAMICS USING BURNT PERMANENT FOREST PLOTS

James M Furlaud, David MJS Bowman

Fire Centre Research Hub, University of Tasmania

UNIVERSITY of TASMANIA

FIRE CENTRE RESEARCH HUB

Tasmania Fire Service

TERN Terrestrial Ecosystem Research Network

Version	Release history	Date
1.0	Initial release of document	25/05/2020

Australian Government
Department of Industry, Innovation and Science

Business Cooperative Research Centres Programme

Publisher:
Bushfire and Natural Hazards CRC

May 2020

Citation: Furlaud J & Bowman D (2020) Understanding post-fire fuel dynamics using burnt permanent forest plots, Bushfire and Natural Hazards CRC, Melbourne.

Cover: McKenzie and Weld Ausplots before and after their respective fires. Source: James Furlaud

TABLE OF CONTENTS

BACKGROUND

TERN AUSPLOTS

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.

TASMANIAN FUEL CHRONOSEQUENCE PLOTS

The Tasmanian Fuel Chronosequence project was set up in 2016 to measure fuel load, structure, and hazard specifically in Tasmanian tall wet eucalypt forests with varying times since previous fire (hereafter referred to as stand-development stages). For the chronosequence plots, 23 permanent plots were set up in forests in four different stand-development stages: sapling, spar, early-mature, and late-mature[3,4]. This contrasted with the Ausplots, which only focused on forests in the early-mature stand-development stage, but covered the entire continent. We measured forests in the sapling stage regenerating following clearfell, burn, and sowing operations, rather than a high-severity fire, as there have been no high-severity fires in Tasmania's southern tall wet forests since 1967. The purpose of these permanent plots was to understand fuel dynamics in Tasmanian tall wet eucalypt forests as a function of time since previous disturbance and to develop a fuel model that could be used in fire behaviour models.

THE FIRES

Between October 2014 and January 2019, low-moderate severity fires burnt eight Ausplots and 12 Chronosequence plots: two in North Queensland, one in northern Tasmania, one in southwest Western Australia, and 16 in Southern Tasmania (figs 1, 2 & 3). This provided an opportunity to measure the reduction in fuel load and hazard caused by low-moderate severity fires, and to get a baseline, post-fire measurement of fuels in wet eucalypt forests. The 20 plots that burned are outlined in tables 1 and 3. The weather conditions during the fires between 2014 and 2017 were extracted from the Bureau of Meteorology (BOM) Australian Digital Forecast Database, and the conditions during the 2019 fire

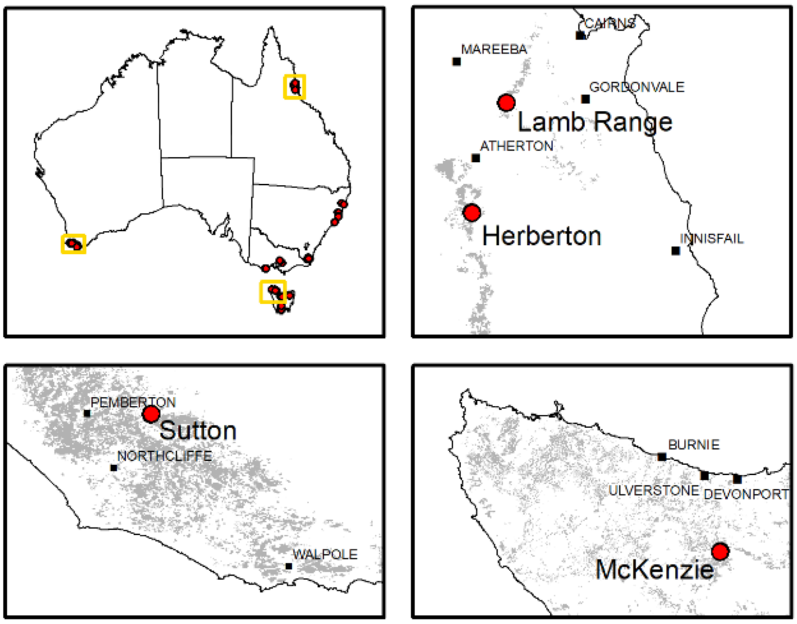


FIGURE 1: MAPS SHOWING: (A) THE LOCATION OF ALL AUSPLOTS (SMALL RED DOTS) AND THE REGIONS IN WHICH THE PLOTS THAT BURNED BEFORE 2018 ARE LOCATED (YELLOW RECTANGLES), AND THE LOCATION OF THESE BURNT PLOTSIN THEIR RESPECTIVE REGIONS, (B) NORTH QUEENSLAND, (C) SOUTHWEST WESTERN AUSTRALIA, AND (C) CENTRAL TASMANIA. THE GREY SHADED AREAS REPRESENT THE EXTENT OF TALL WET EUCALYPT FOREST IN THE REGION.

was extracted from (BOM) the Barra reanalysis project. These conditions are outlined in tables 2 & 3.

The northern 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.[5] Though the fire garnered international headlines for its destruction of fire-intolerant ecosystems such as cushion plant, pencil pine, and king-billy pine,[6] the majority of the fire burned in wet and dry eucalypt forest (fig 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 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.[7] 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.

TABLE 1: SUMMARY INFORMATION OF THE FOUR 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 INCLUDED. NOTE THAT THE FOUR AUSPLOTS THAT BURNED IN 2019 ARE PRESENTED IN TABLE 3

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

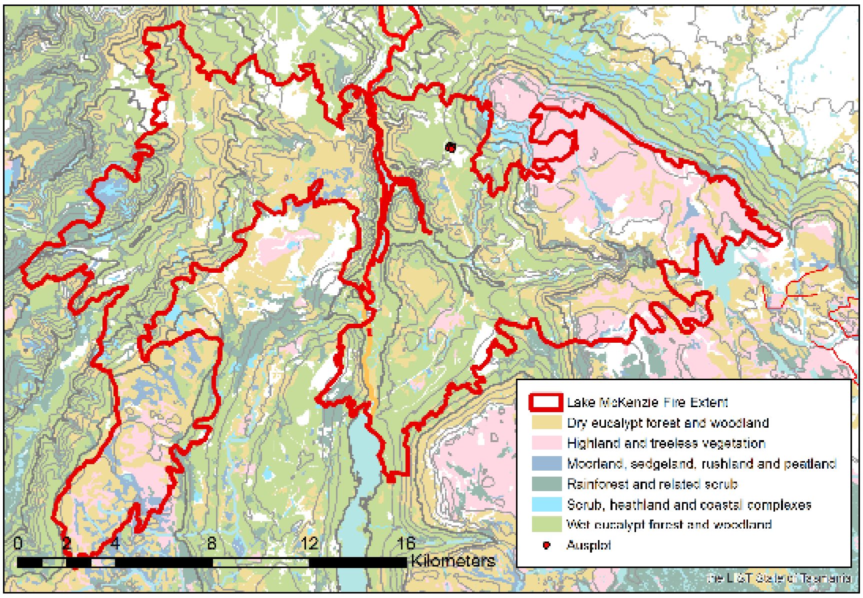


FIGURE 2: MAP SHOWING EXTENT OF THE LAKE MCKENZIE FIRE, THE LOCATION OF THE MCKENZIE AUSPLOT, AND THE DISTRIBUTION OF THE MAJOR NATIVE VEGETATION TYPES IN THE REGION. DATA SOURCES: TASMANIA FIRE SERVICE[3] AND TASVEG 3.0[7]

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.[8] 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.[9] It also was performed on a day with quite mild fire weather, with a forecast FFDI of 11.

The Riveaux Road Fire in started on 15 January 2019 and burned 63,769 ha over the course of roughly one month. In the lead up to this fire, Tasmania had experienced its driest January since 1939, and parts of southern Tasmania experienced their driest January on record.[10] The fire burned through forest dominated by *Eucalyptus regnans* and *E. obliqua* with both rainforest and broadleaf understoreys. The area burnt included 12 Chronosequence plots and four Ausplots (which were located directly adjacent to four of the Chronosequence plots). The period in the second half of January, during which all but one of the plots burned, was marked by extremely variable fire weather,

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.

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

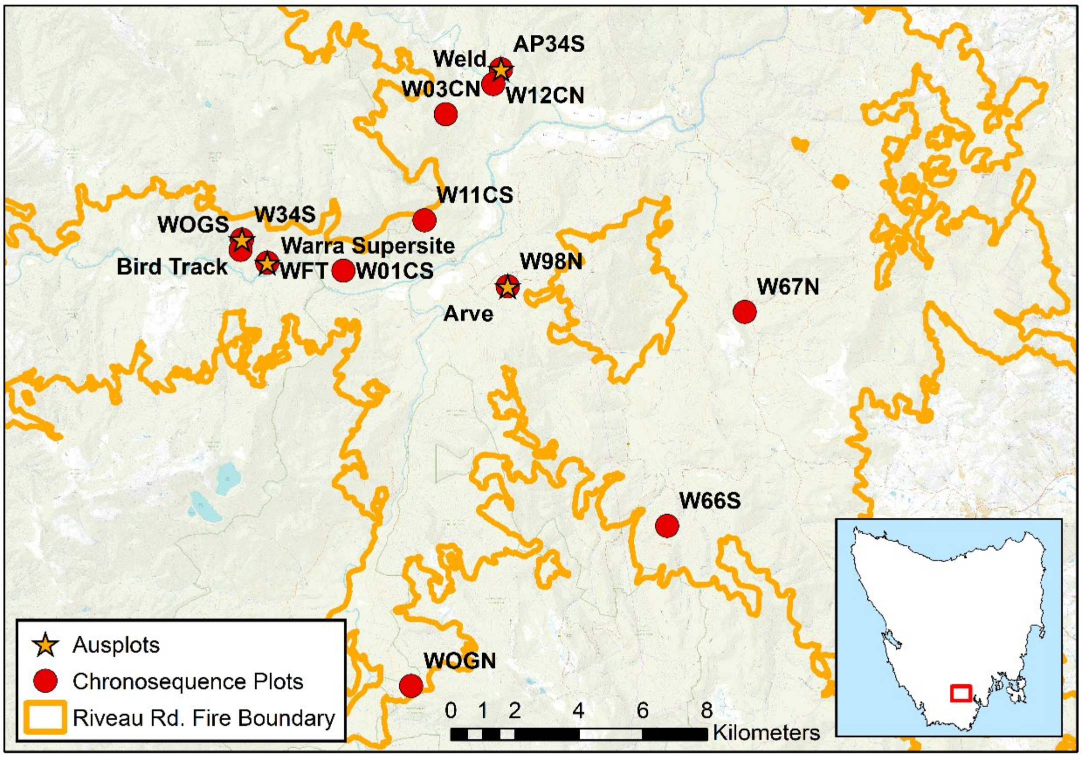


FIGURE 3: MAP OF THE LOCATION OF THE 4 AUSPLOTS (STARS) AND 12 CHRONOSEQUENCE PLOTS (CIRCLES) BURNED IN THE 2019 RIVEAUX RD FIRE

with daily maximum FFDI varying between 10 and 40. The potential weather profiles for each site are listed in table 3. The fire itself was marked by a high level of variation in fire severity, with patchy crown fires and extensive areas of only surface fires. While the FFDI throughout the period of the fire was highly variable, all of the permanent plots that burned did so on mild fire weather days (table 3).

These fires presented us with an excellent opportunity to obtain fuel load, structure, and hazard measurements both directly before and after low severity fires. Not only would such measurements provide an estimate of how much fuel is consumed in planned burns, but such fuels data could be used to validate fire behaviour models, whose utility in these forests is poorly understood. Further, fine scale measurements of fire severity, when associated with fuels data from directly before the fire will allow us to untangle the effect of fuels on fire severity in a forest type where flammability is poorly understood.

Lastly, 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.

TABLE 2: ENVIRONMENTAL, STRUCTURAL, AND FLORISTIC ATTRIBUTES OF THE 12 CHRONOSEQUENCE PLOTS THAT BURNED IN THE 2019 RIVEAUX ROAD FIRE. DATE OF ORIGINAL MEASUREMENT, ALONG WITH REMEASUREMENT ARE ALSO GIVEN. LASTLY THE RANGE OF DATES IN 32019 DURING WHICH EACH PLOT COULD HAVE BURNED, AND THE RANGE OF ASSOCIATED FFDI VALUES, ARE GIVEN. NOTE THAT THE FOUR AUSPLOTS THAT BURNED IN THIS FIRE WERE COL-LOCATED WITH FOUR CHRONOSEQUENCE PLOTS. CO-LOCATED AUSPLOTS ARE GIVEN IN PARNTHESES.

Site	Eleva-tion (m)	Mean Annual Temperature (°C)	Mean Annual Precipitation (mm)	Stand-Development Stage	Maximum Overstorey Height (m)	Dominant Species	Date of original measurement	Date of remeasure-ment	Date Range of Burn	Lowest possible FFDI	Highest possible FFDI
AP34S (Weld)	60	11	1228	Early Mature	51.8	*E. regnans*	28/02/2016	9/01/2020	26-27 Jan	4	13
W01CS	130	11	1358	Sapling	12.8	*E. obliqua*	11/04/2016	14/11/2019	26-27 Jan	3	11
W03CN	155	11	1322	Sapling	16.7	*E. obliqua*	21/04/2016	10/12/2019	27-29 Jan	3	13
W11CS	218	11	1368	Sapling	None	*E. obliqua*	20/04/2016	18/01/2020	28-29 Jan	3	11
W12CN	87	11	1202	Sapling	10.5	*E. obliqua*	24/04/2016	8/01/2020	26-27 Jan	3	13
W34S (Bird Track)	195	10	1466	Early Mature	51	*E. obliqua*	11/02/2016	29/01/2020	22-23 Jan	3	13
W66S	288	10	1385	Spar	28.9	*E. obliqua/ E. regnans*	3/03/2016	21/11/2019	26-27 Jan	3	14
W67N	132	11	1210	Spar	29.3	*E. obliqua*	3/02/2016	16/12/2019	26-27 Jan	3	13
W98N (Arve)	224	10	1381	Early Mature	49.6	*E. obliqua*	17/02/2016	7/11/2019	21-22 Jan	4	17
WFT (Warra Supersite)	88	11	1364	Early Mature	52.2	*E. obliqua*	3/02/2016	19/11/2019	28 Jan	4	14
WOGN	385	9	1534	Late Mature	36.6	*E. obliqua*	3/03/2016	1/21/20	2-3 Feb	3	7
WOGS	107	10	1466	Late Mature	25.5	*E. obliqua*	10/02/2016	30/01/2020	22-24 Jan	5	17

OBJECTIVES

The main goal of this study is to obtain empirical measurements of fuel load, structure and hazard 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 fuels 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 fire severity and fuel accumulation in wet eucalypt forests related to other BNHCRC studies attempting to measure both fuel accumulation and the drivers of fire severity in wet forests.

CURRENT STATE OF KNOWLEDGE

The flammability of tall wet eucalypt forests is poorly understood. A globally unique forest type, these forests consist of a highly-flammable *Eucalyptus* overstorey and a moist, non-flammable understorey consisting of rainforest and broadleadf trees and shrubs.[11,] As a result, these forests are rarely available to burn, and almost no data exists on flammability and fire behaviour. While current fire behaviour models assume that fuel load and hence flammability increase asymptotically as a function of time since previous fire, [12,13] there is much debate over whether this is the true trajectory of flammability in these forests.[14,15,16] Understanding how fire severity is influenced by fuels and time since fire is a critical question in these forests.

As the rate of spread and intensity of a fire is a function of fuels, fire weather and topography,[17] and as only the latter can be physically manipulated, the effect of fire on fuel loads is extremely important to understand. Low-severity fires are known to reduce surface fine fuels loads across a landscape in certain forest types, so intentionally lighting low-severity fires (i.e. planned burns), will increase the encounter rate of wildfires with low fuel load areas.[7] However the effect of low-severity fires in wetter forests is mostly unstudied. While reducing fuel ages has been shown to reduce both the extent and incidence of unplanned fires,[18,19,20] 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,[8,21] 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 project will contribute a valuable high-resolution field-based validation dataset for the BNHCRC project *Using pre and post fire LiDAR to assess the severity of the 2019 Tasmanian Bushfires*. This project will create, among other things, a high-resolution fire-severity map of the Riveaux Road Fire. With these data, we will be able to perform geospatial analyses to untangle the drivers of fire severity during this bushfire. Importantly the area burned in the fire includes the WARRA silvicultural experiment, in which a number of silvicultural treatments were trialled in a small area. This will allow an investigation into the effects of different silvicultural practices on flammability and fire severity in tall wet *Euclayptus* forests.

This study is will also 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 characterise flammability in tall wet *Euclayptus* forest and better represent their fuels in fire behaviour models. This project relies heavily on data from both the Ausplots and Chronosequence plots to describe, using a modelling approach, the fire regime of these forests. This data will provide critical validation of this description. More specifically, this study will add a valuable validation section to a forthcoming peer-reviewed paper providing a first-ever explicit description of the fire regime of mature wet *Eucalyptus* forests across Australia.

RESEARCH QUESTIONS

This study plans to focus on three major research questions:

- What is the effect of low- and moderate-severity fires on fuel load and structure in tall wet eucalypt forests?
- What is the risk reduction associated with such fires?
- How does fuel age, structure, and load affect fire severity?

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 then returned to the plots to measure fuels in the summer of 2014-15. We established the Chronosequence plots in the autumn of 2016. We re-measured the plots that had burnt in November 2016, November 2017, and November 2019 – January 2020. The methodology for the fuel surveys of both the Ausplots and the Chronosequence plots was derived from NASA-funded fuel surveys.[22]

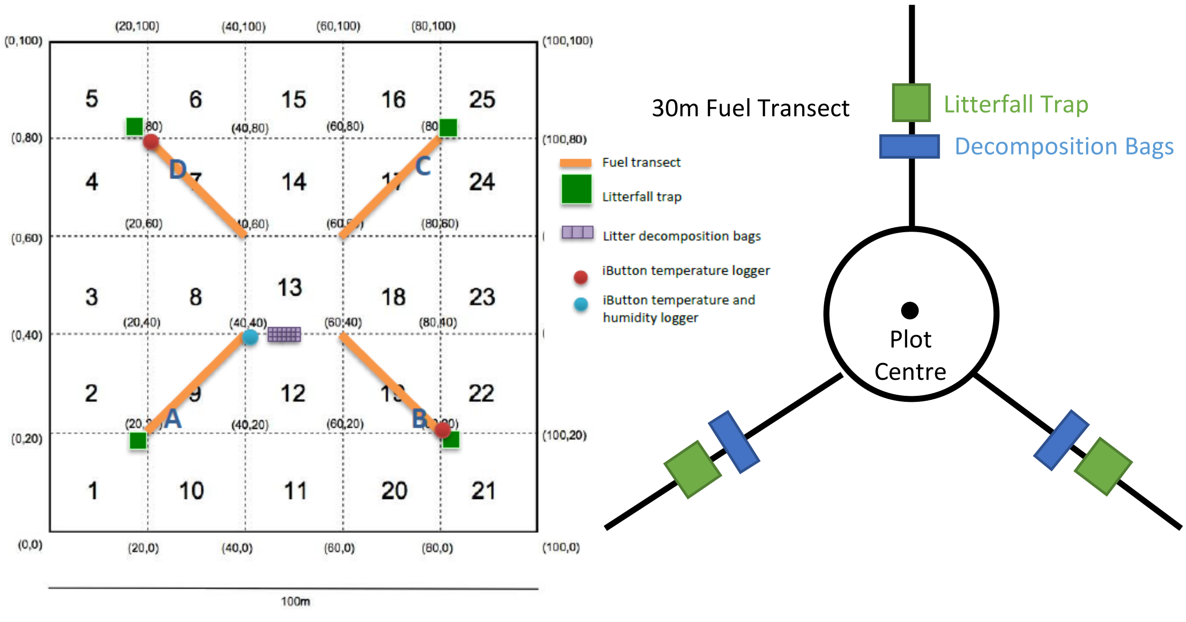
FUEL SURVEYS

From October 2014 – February 2016, we performed fuel load surveys along four 28.3 m transects in each of the Forest Ausplots (fig 4a). From February – July 2016, we performed fuel surveys along three 30m transects at each Chronosequence plot (fig 4b). We used the transects to measure surface, near surface, and elevated fuel loads (in tonnes per hectare; t/ha) and structure. We measured the input and output rates for surface fine fuels using litterfall traps and decomposition bags. Lastly, we measured the temperature and humidity in the understorey in the understorey microclimate using iButtons. A detailed account of all the fuel survey techniques for the Ausplots Forests Fuels Survey can be found in the field manual.[23] Not all the Ausplot data from these methods is presented in the results, but all the data will be available on the AEKOS TERN Data Portal.[24]

Surface and Near-surface Fuels

Quadrats for surface and near-surface fuels

We set up 1x1 m quadrats between the 7-8m and 21-22m marks along the transect tape. We destructively sampled all fuels in the surface and near-surface layers. We defined surface fine fuels as all dead, detached leaves, bark and twigs <0.6cm in diameter. For the Ausplots we defined near-surface fuels as all non-woody plants (not including ferns), vines, and grasses. For the Chronosequence plots we defined near-surface fuels as *all* plants <1.3m tall and *all* ferns (except tree ferns) and grasses. For the Ausplots, we measured the fresh weight of all collected materials on site along with a subsample of at least 350g of each fuel category from each quadrat. We then oven-dried these subsamples to obtain a dry weight to fresh weight ratio. For the Chronosequence plots we oven-dried all collected samples. We oven-dried samples to a constant weight at 70°C. Lastly we measured the depth of the topmost organic layer in the soil.



(A) (B)

FIGURE 4: DIAGRAM OF THE LOCATION OF THE FUEL TRANSECTS, LITTERFALL TRAPS, AND DECOMPOSITION BAGS IN (A) THE AUSPLOTS AND (B) THE CHRONOSEQUENCE PLOTS

Litterfall Traps and Decomposition Bags

To measure the input and output rates of fine fuel, we set up litterfall traps and decomposition bags as indicated in fig 5. The litterfall traps were constructed of 32mm diameter PVC pipe 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 (Fig 5a). The decomposition bags were 20cm x 20cm, constructed of 152 μm mesh, sewn or heat-sealed together on three sides. We filled 15 of the bags with roughly 10g (or 25g for the Chronosequence plots) 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. For the Ausplots we pinned all 21 bags into the ground near the beginning of the first transect using weed mat pegs (fig 5b). For the Chronosequence plots we pined 7 bags (5 litter and 2 calico) at the midpoint of each transect. 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[25,26]: (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

(A)

(B)

FIGURE 5: 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]

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 fig 6. We then used the standard technique for converting the diameter of downed logs into t/ha, assuming a relative density of 0.4.[27,28]

Elevated Fuel Layer

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 to the tape. For the Ausplots, we considered any plant that had a stem that "snapped" (namely woody plants, ferns, and tree ferns) to be a shrub. For the Chronosequence plots we considered any plant >1.3m height (and all tree ferns) to be a "shrub". Importantly, for the Chronosequence plots, all ground ferns, regardless of height, were considered part of the near-surface layer, and not measured at this stage. In all plots, any plant, other than tree ferns, that had a DBH >10cm was considered to be part of the overstorey and not measured at this stage. 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. For the Chronosequence plots we also measured the basal diameter, and canopy dimensions for each shrub.

We grouped all shrubs into one of four growth form categories: tree, shrub, multi-stem tree, tree fern, or fern (Ausplots only). We measured the length and width of a rectangle bounding the group of five shrubs so we obtain per hectare estimates (fig 7). 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.[29,30]

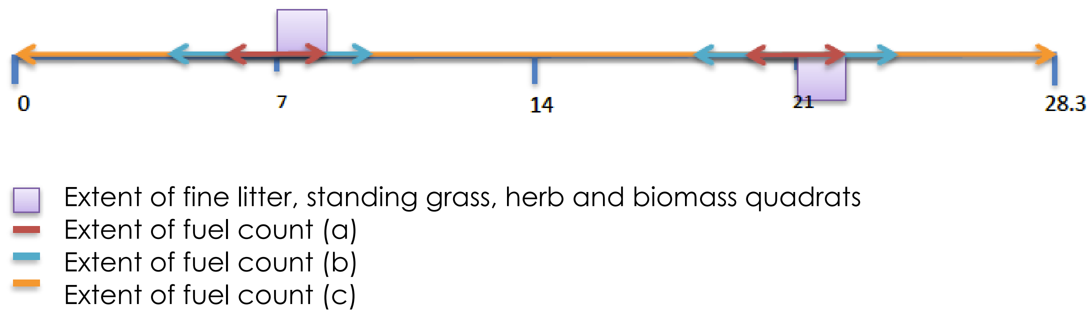


FIGURE 6: EXTENT OF WOODY FUEL COUNTS AND FINE FUEL QUADRTATS[2]

REMEASUREMENT OF BURNT PLOTS

In November of 2016 and 2017, and November 2019 - January 2020, we returned to the eight Ausplots and 12 Chronosequence plots 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 subsection (a; fig 6), 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. Additionally, we did not set up decomposition bags or literfall traps in the burnt plots.

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. After the fires there were a significant number of dead standing shrubs in the elevated layer of all plots, so we repeated the elevated fuels methodology for dead, standing shrubs. For the Ausplots, as we had already done for the Chronosequence plots, we measured the basal diameters of all shrubs. When shrubs had multiple stems we

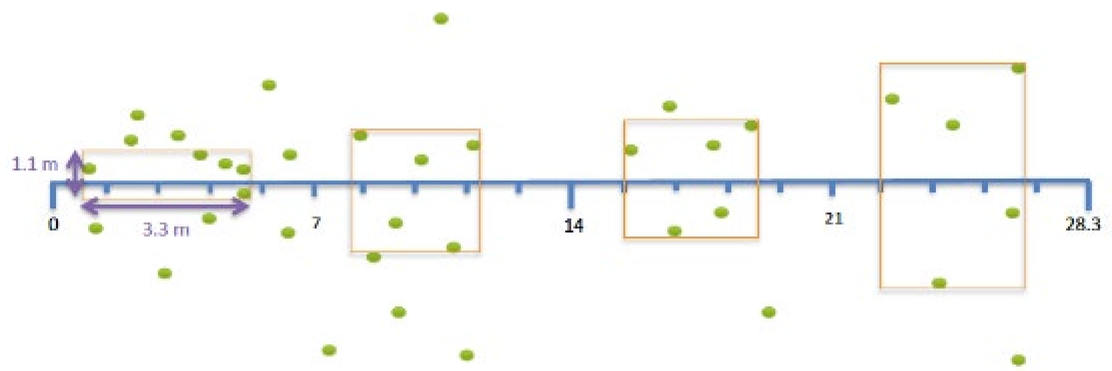


FIGURE 7: DIAGRAM OF CHOICE OF SHRUBS AND MEASUREMENT OF SURROUNDING RECTANGLE.[2]

measured the diameter of the largest stem, then counted the number of additional stems and estimated their average diameter.

Fire Severity

In the Ausplots, to measure severity of the fires, we measured the DBH of each overstorey tree (considered any plant with a DBH >10cm) within the 20 x 20m subplot containing each transect (fig 4a). We also measured the height of charring on each tree (except those with fibrous bark) using a vertex hypsometer.

For the Chronosequence plots, on each dead plant in the elevated layer, we measured the height of charring and diameter of any burnt branch tips between 0.7 and 1.3m aboveground (if applicable). We also took the same measurements on the roughly ten closest plants to the transect (up to 3m away) that were not captured by the elevated fuels methodology.

QUALITATIVE HAZARD ASSESSMENT

In the Chronosequence plots, we also performed a qualitative assessment of fire hazard according to the Victorian Fuel Hazard Assessment Guide.[31] This involved making percent cover, percent dead, and qualitative hazard assessments for each fuel layer. We performed these in both our pre-fire and post-fire measurements.

FINDINGS

Preliminarily, this study has revealed that a consistent effect of low-moderate severity fires in tall, wet *Eucalyptus* forests is to kill, but not consume, the fire-sensitive understorey. This resulted in a new deposition of fine surface fuels within the first 10 months after a fire, and a substantial amount of dead standing coarse fuels, which will eventually fall to the surface. Further, the thinning of elevated fuels will likely dry out the understorey, potentially leaving these forests vulnerable to future fires.

SURFACE AND NEAR-SURFACE FUELS

Fine and Coarse Fuels

Among the most interesting results in this study is that the surface fine fuel loads quickly re-accumulated after the fire. All Ausplots and Chronosequence plots had accumulated roughly 5 t/ha of surface fine fuels within the first year after a fire (figs 8a, 9). Further, in the Queensland Ausplot Lamb Range, where 18 months had passed since the fire, the fuel load had re-accumulated to 10 t/ha, suggesting these fuels continue to accumulate quickly. This indicates that the effectiveness of low-severity fires in reducing fuel load in these forests is dependent on the pre-fire fuel load. For example, in the plot Western Australian plot Sutton, the pre-fire fuel load was almost 40 t/ha, whereas in the Queensland Ausplot Herberton, and the Chronosequence plots W12CN and W66S, reductions in fuel load were minimal (figs 8a, 9) Given the primary importance of fine fuels in driving fire behaviour, this is potentially an important result regarding the effectiveness of low-severity fires at reducing fire hazard in different climates and stand development stages in wet *Eucalyptus* forests.

The trend among grasses is less consistent (fig 8b). Only two Queensland plots had substantial grass fuel before the fires. Grasses seem to have quickly regrown in Herberton, where the site was being colonised by the highly flammable *Imperata cylindrica*[32], but in Lamb Range the fire seems to have successfully eliminated grasses. Meanwhile the fires seemed to substantially reduce coarse fuel loads in every site (fig 8c).

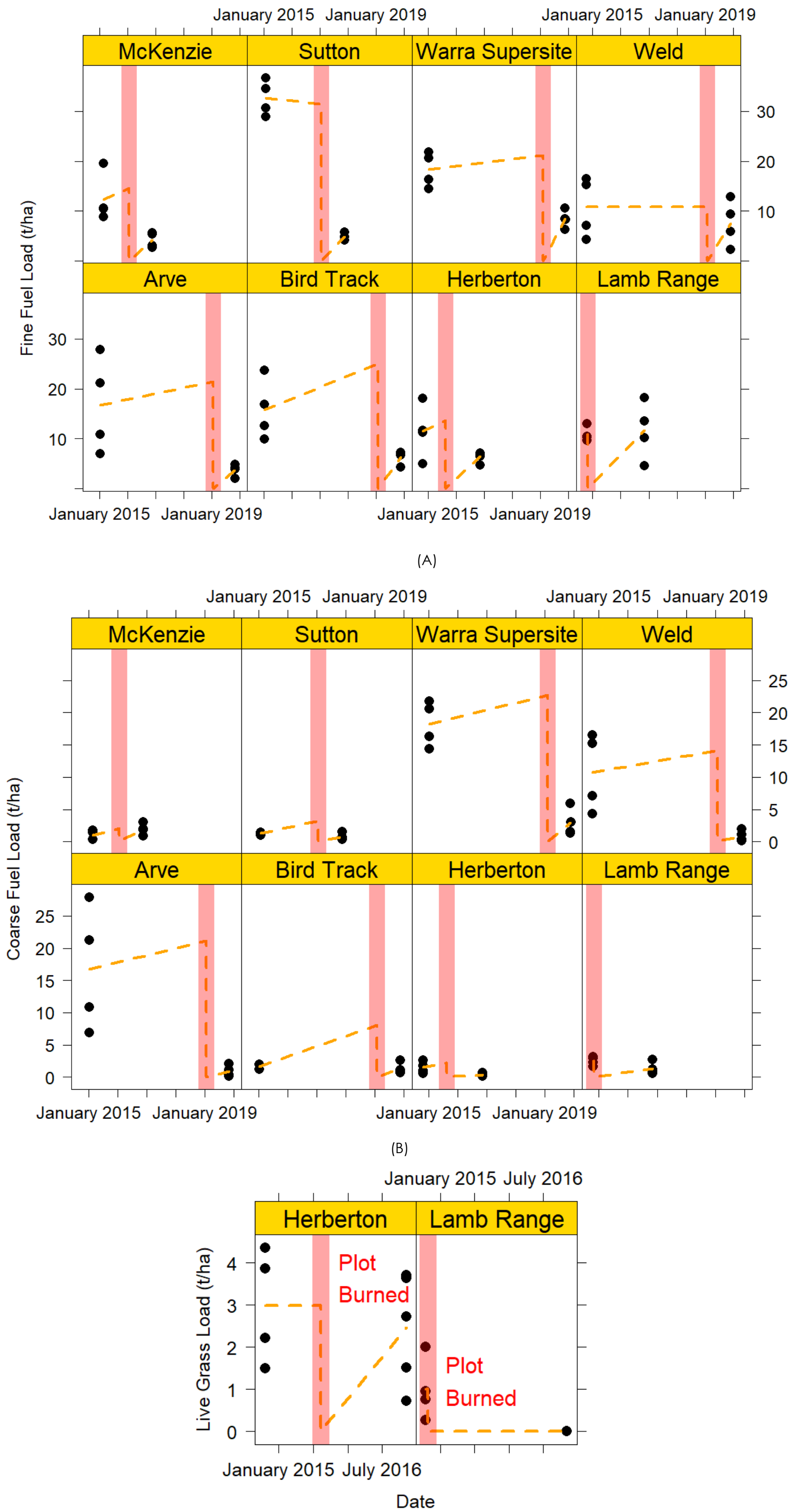


FIGURE 8: TIMELINE OF SURFACE FUEL LOADS (IN TONNES PER HECTARE) AT THE AUSPLOTS. (A) DEPICTS FINE FUELS, (B) COARSE WOODY FUELS (0.6-2.5 CM DIAMETER, 1 HOUR DRYING CLASS) AND (C) LIVE GRASS. THE BLACK DOTS REPRESENT INDIVIDUAL QUADRATS, AND THE ORANGE DOTTEDD LINE REPRTESENTS THE ESTIMATED FUEL ACCUMULATION PATTERN. FUEL ACCUMULATION WAS INFERRED FROM PREVIOUSLY MEASURED RATES (SEE METHODS) AND ASSUMED COMPLETE CONSUMPTION THE THREE FUEL TYPES DURING THE BURN. SHADED RED BOXES REPRESENT THE ESTIMATED TIME OF THE FIRE.

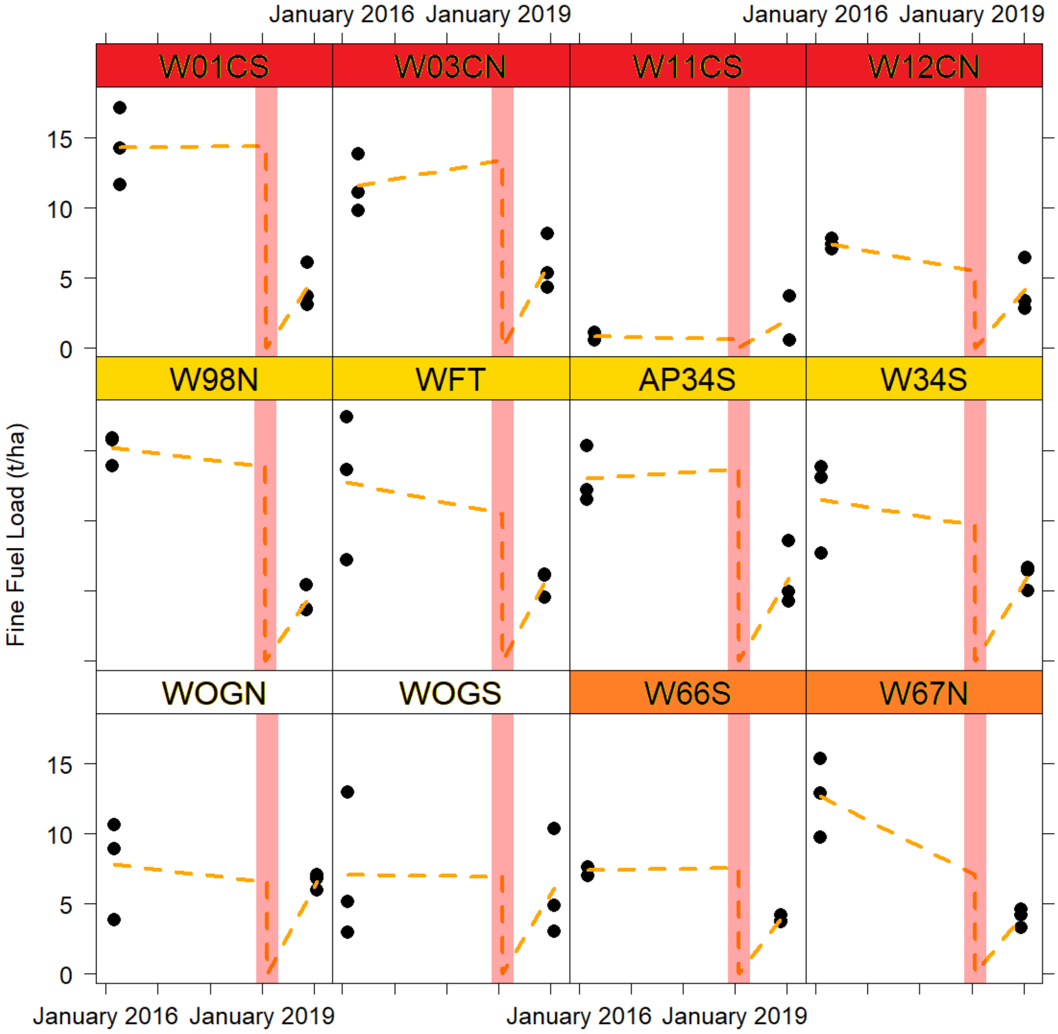


FIGURE 9: TIMELINE OF SURFACE FINE FUEL LOADS (IN TONNES PER HECTARE) AT THE CHRONOSEQUENCE PLOTS. THE BLACK DOTS REPRESENT INDIVIDUAL QUADRATS, AND THE ORANGE DOTTEDD LINE REPRTESENTS THE ESTIMATED FUEL ACCUMULATION PATTERN. FUEL ACCUMULATION WAS INFERRED FROM PREVIOUSLY MEASURED RATES (SEE METHODS) AND ASSUMED COMPLETE CONSUMPTION THE THREE FUEL TYPES DURING THE BURN. SHADED RED BOXES REPRESENT THE ESTIMATED TIME OF THE FIRE. PANEL COLOUR REPRESENTS STAND DEVELOPMENT STAGE: LATE-MATURE (WHITE), EARLY-MATURE (YELLOW), SPAR (ORANGE), AND SAPLING (RED)

ELEVATED FUELS

Perhaps the most consistent effect of the low-moderate severity fires across all plots was the death, but not combustion, of most plants in the fire-sensitive understorey. The exception to this were tree ferns, all of which paradoxically combusted yet survived. This is apparent in the Ausplots through a reduction of the fuel load and bulk density of live fine fuels in the elevated layer (fig 10). In the Chronosequence plots, this is apparent through the hazard assessment of the elevated layer (fig 11), which revealed a decrease in estimated percent cover and an increase in estimated percent dead fuels to above 50% in nine plots. This would explain the quick re-accumulations of fine fuels after the fires, as all the dead plants that were not consumed by the fire would quickly drop their leaves. Further, analysis of basal area of dead standing fuels revealed a large amount of standing dead fuels in most plots (fig 12), suggesting that a large deposition of coarse fuels onto the surface is yet to come. The prevalence of dead fuels in the elevated layer seems to be especially high in the sapling and early-mature stand development stage.

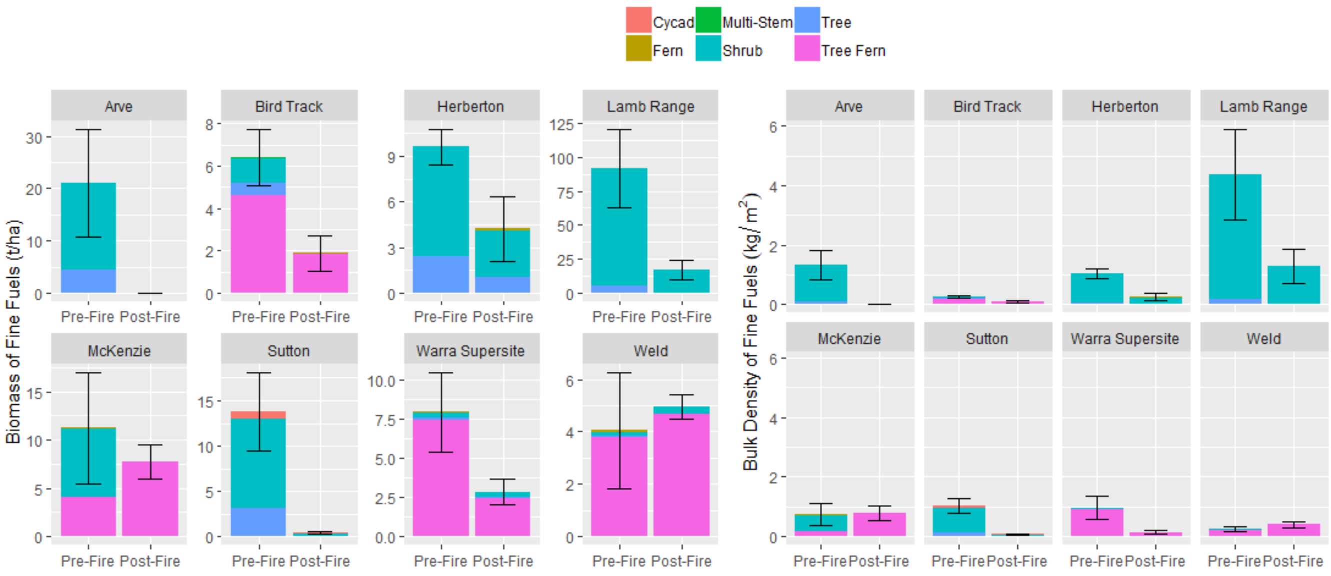


FIGURE 10: (A) ESTIMATED BIOMASS IN TONNES PER HECTARE OF LIVE FINE FUELS IN THE ELEVATED LAYER AT EACH SITE. LIVE FINE FUELS ARE DEFINED AS ALL FOLIAGE AND TWIGS <0.6CM DIAMETER. (B) ESTIMATED BULK DENSITY OF LIVE FINE FUELS IN THE ELEVATED LAYER BASED ON THE AVERAGE PLANT HEIGHT IN EACH SUBPLOT. ERROR BARS REPRESENT ONE STANDARD ERROR

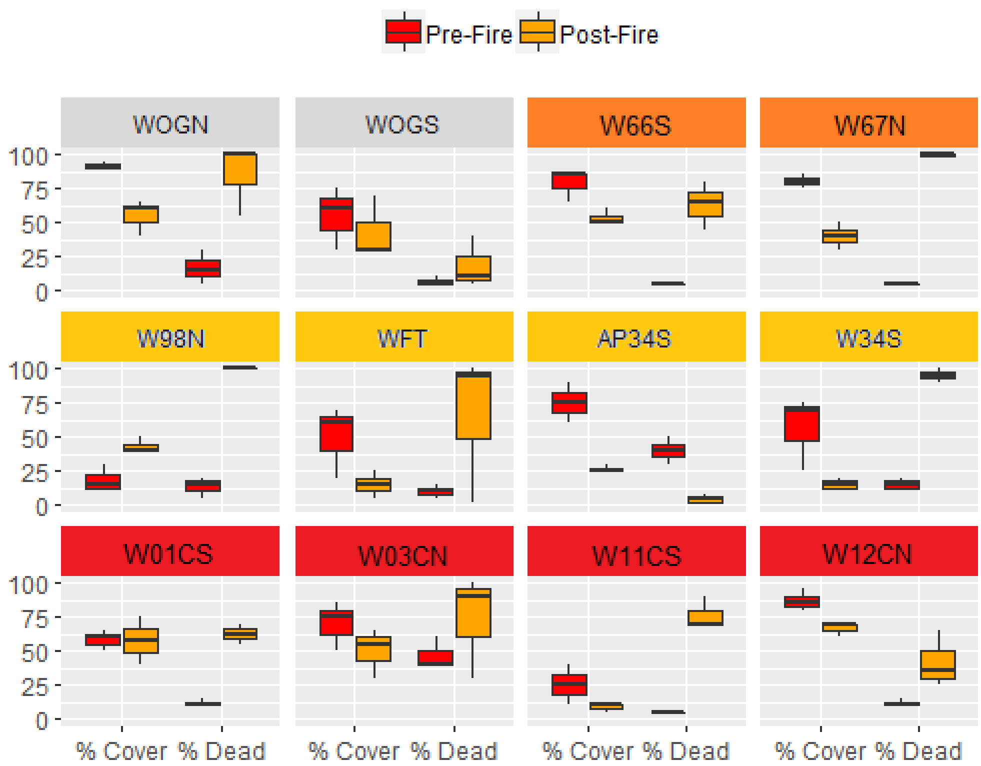


FIGURE 11: ESTIMATED PERCENT DEAD FUELS AND PERCENT COVER IN THE ELEVATED LAYER BEFORE AND AFTER THE FIRE IN THE CHRONOSEQUENCE PLOTS. PANEL COLOUR REPRESENTS STAND DEVELOPMENT STAGE: LATE-MATURE (GREY), EARLY-MATURE (YELLOW), SPAR (ORANGE), AND SAPLING (RED)

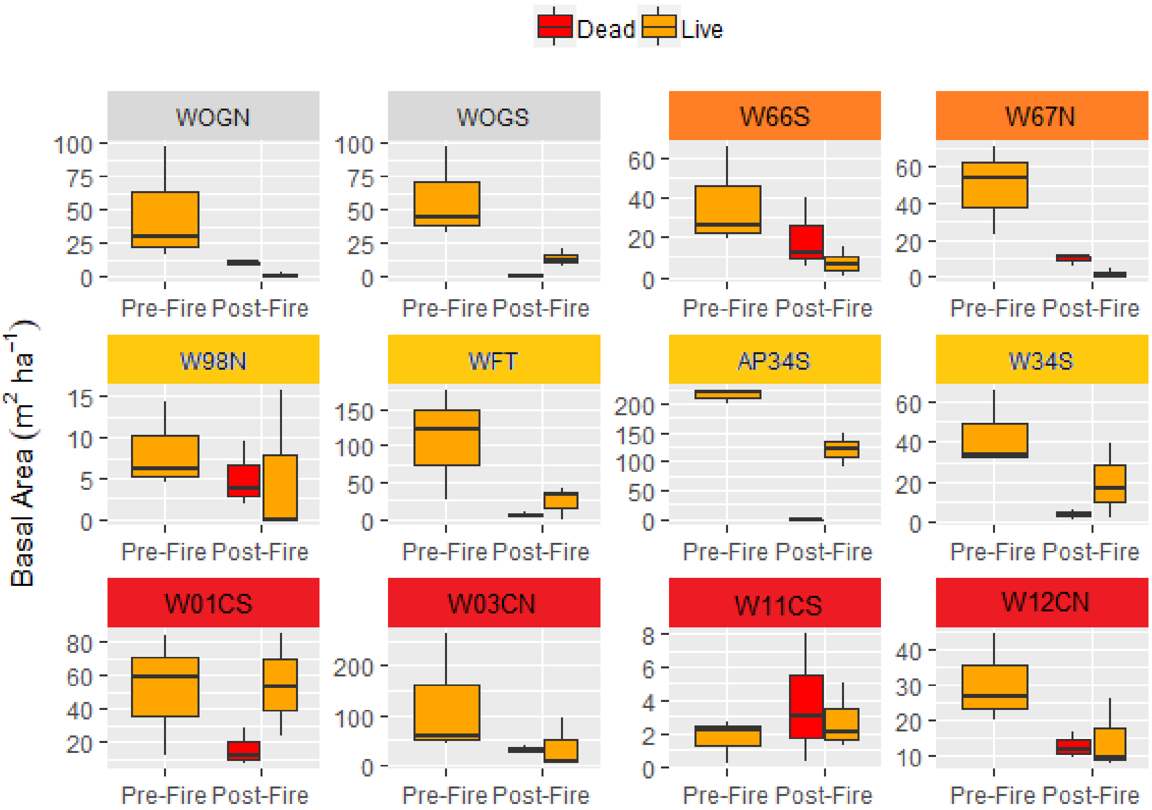


FIGURE 12: BASAL AREA PER HECTARE OF LIVE (ORANGE BOXES) AND DEAD (RED BOXES) STANDING PLANTS IN THE ELEVATED LAYER BEFORE AND AFTER THE FIRE IN THE CHRONOSEQUENCE PLOTS. PANEL COLOUR REPRESENTS STAND DEVELOPMENT STAGE: LATE-MATURE (GREY), EARLY-MATURE (YELLOW), SPAR (ORANGE), AND SAPLING (RED)

THE EFFECT OF LOW-SEVERITY FIRES ON FIRE HAZARD

Given the quick re-accumulation of leaf litter resulting from the deposition that is suggested by this data, and given the fuel-rich nature of tall wet *Eucalyptus* forests, these forests are likely to have adequate fuel loads to sustain a fire relatively quickly after a low-severity burn. Further, the reduction in the percent cover and bulk density of understorey plants indicates a likely removal of the understorey microclimate effect characteristic of these forests.[33,34] This dried-out understorey and adequate fuel load could indicate that these forests are vulnerable to a second fire in quick succession, especially given an increasing dryness of the Tasmanian landscape due to climate change.[35] Such fires in quick succession have been shown to be catastrophic in obligate-seeder dominated wet forests, especially those in the sapling stage,[36] and could be problematic in reprouter dominated forests as well.[37] However, these results are preliminary and more analysis needs to be conducted before any strong conclusions can be drawn.

FUTURE USE OF OUTCOMES

The next step is to use these data in actual fire behaviour models such as the McArthur model to compare predicted flame heights to the char heights we measured on dead plants. This will provide a much-needed validation of fire behaviour models in wet *Eucalyptus* forest, as little data on fire behaviour exists for these forests. We can also use such models to asses the vulnerability of these forests to a second fire in the years immediately after a burn. To do this we need to develop allometric equations to predict the biomass of dead standing plants so we can get a complete estimate of elevated fuel loads.

This data, in combination with the larger project *Using pre and post fire LiDAR to assess the severity of the 2019 Tasmanian Bushfires*, will help create a high-resolution fire severity map of the Riveaux Rd fire. From this we will be able to conduct landscape analyses to untangle the drivers of fire severity in these forests. Given the highly-managed nature of the area burned in this fire, this could represent an ideal natural experiment to investigate the effect of silvicultural practices on fire hazard. This is quite relevant given the discussion of using forest management as a fuel reduction tactic that followed the 2020 Australian bushfire crisis (SMH article).

Lastly, our data is the starting point for developing a database of pre- and post-fire fuel measurements in permanent plots. We already have 16 such plots measured, and given that there are 55 other plots in the two networks discussed in this report, and that 8 more plots have burned in January 2020, this could become a valuable database, especially given the lack of fire behaviour data from these forests.

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 Mifsud BM. Victoria's tallest trees. Australian Forestry 66: 197-205, 2003.
4 Ashton DH. The development of even-aged stands of F. Muell. in central Victoria. Australian journal of botany 24, 1976.
5 AFAC Independent Operational Review: A review of the management of the Tasmanian fires of January 2016. Australasian Fire and Emergency Service Authorities Council 2016.
6 Slezak M. Tasmanian bushfires 'worst crisis in decades' for world heritage forests. In: The Guardian Australia, 2016.
7 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.
8 Goetze K, Personal Communication, Queensland Parks and Wildlife Service 31 January 2017
9 McCaw L, Personal Communication, Western Australia Department of Parks and Wildlife, 13 November 2017
10 Australasian Fire and Emergency Service Authorities Council: AFAC INDEPENDENT OPERATIONAL REVIEW: A review of the management of the Tasmanian fires of December 2018 – March 2019. Melbourne, VIC, 2019.
11 Wardell-Johnson G, Neldner J, Balmer J. Wet Sclerophyll forests, in Keith D (ed): Australian Vegetation. Cambridge, UK: Cambridge University Press, 2017, pp281-313.
12 Gould J, Cruz M. Australian fuel classification: Stage II. East Melbourne, VIC Australia: Australasian Fire and Emergency Services Council (AFAC) and the Commowealth Science and Industrial Research Organisation (CSIRO), 2012.
13 Bradstock RA, Hammill KA, Collins L, Price O. Effects of weather, fuel and terrain on fire severity in topographically diverse landscapes of south-eastern Australia. Landscape Ecology 25: 607-619, 2009.
14 Attiwill P, Ryan M, Burrows N, Cheney N, McCaw L, Neyland M, et al. Timber harvesting does not increase fire risk and severity in wet eucalypt forests of southern Australia. Conservation Letters 7: 341-354, 2014.
15 Cawson JG, Duff TJ, Swan MH, Penman TD. Wildfire in wet sclerophyll forests: the interplay between disturbances and fuel dynamics. Ecosphere 9, 2018.
16 Taylor C, McCarthy MA, Lindenmayer DB. Nonlinear Effects of Stand Age on Fire Severity. Conservation Letters 7: 355-370, 2014.
17 Fernandes PM, Botelho HS. A review of burning effectiveness in fire hazard reduction. International Journal of wildland fire 2003; 12: 117-28.
18 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.
19 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.
20 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.
21 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.
22 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.
23 Wood S, Stephens H, Foulkes J, Ebsworth E, Bowman D. Ausplots Forest Monitoring Network: Survey Protocols Manual. Terrestrial Ecosystem Research Network (TERN), 2014.
24 Terrestrial Ecosystem Research Network AEKOS Data Portal; [cited 9 March 2018]. Available from: http://aekos.org.au/index.html#/home
25 Brown JK. Handbook for inventorying downed woody material. 1974.
26 Fosberg MA. Drying rates of heartwood below fiber saturation. Forest Science 1970; 16: 57-63.
27 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.
28 Mackensen J, Bauhus J. The Decay Of Coarse Woody Debris. In: National Carbon Accounting System, Australian Greenhouse Office, 1999.
29 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.
30 Falster DS, Markesteijn L, Poorter L, Sterck FJ, Anten NP. BAAD: a Biomass And Allometry Database for woody plants. Ecology. 2015;96(5):1445.
31 Hines F, Tolhurst KG, Wilson AA, McCarthy GJ. Overall fuel hazard assessment guide: Victorian Government, Department of Sustainability and Environment, 2010.

32 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.
33 Little JK, Prior LD, Williamson GJ, Williams SE, Bowman DM: Fire weather risk differs across rain forest—savanna boundaries in the humid tropics of north-eastern Australia. Austral Ecology 37: 915-925, 2012.
34 Nyman P, Metzen D, Noske PJ, Lane PNJ, Sheridan GJ. Quantifying the effects of topographic aspect on water content and temperature in fine surface fuel. International Journal of Wildland Fire 24: 1129-1142, 2015.
35 Fox-Hughes P, Harris R, Lee G, Grose M, Bindoff N: Future fire danger climatology for Tasmania, Australia, using a dynamically downscaled regional climate model. International Journal of Wildland Fire 23: 309, 2014.
36 Bowman DMJS, Murphy BP, Neyland DLJ, Williamson GJ, Prior LD: Abrupt fire regime change may cause landscape-wide loss of mature obligate seeder forests. Global Change Biology 20: 1008-1015, 2014.
37 Fairman TA, Nitschke CR, Bennett LT: Too much, too soon? A review of the effects of increasing wildfire frequency on tree mortality and regeneration in temperate eucalypt forests. International Journal of Wildland Fire 25: 831-848, 2016.