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UNDERSTANDING POST-FIRE FUEL DYNAMICS USING BURNT PERMANENT FOREST PLOTS

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TERN
Terrestrial Ecosystem Research Network

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

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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). This contrasted with the Ausplots, which only focused on forests in the early-mature stand-development stage, but covered the entire continent. 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]. 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 February 2020, low-moderate severity fires burnt 12 Ausplots and 12 Chronosequence plots: two in North Queensland, one in northern Tasmania, in southwest Western Australia, 16 in Southern Tasmania, and four in southern New South Wales (figs 1-4). 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 24 plots that burned are outlined in tables 1-3. 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

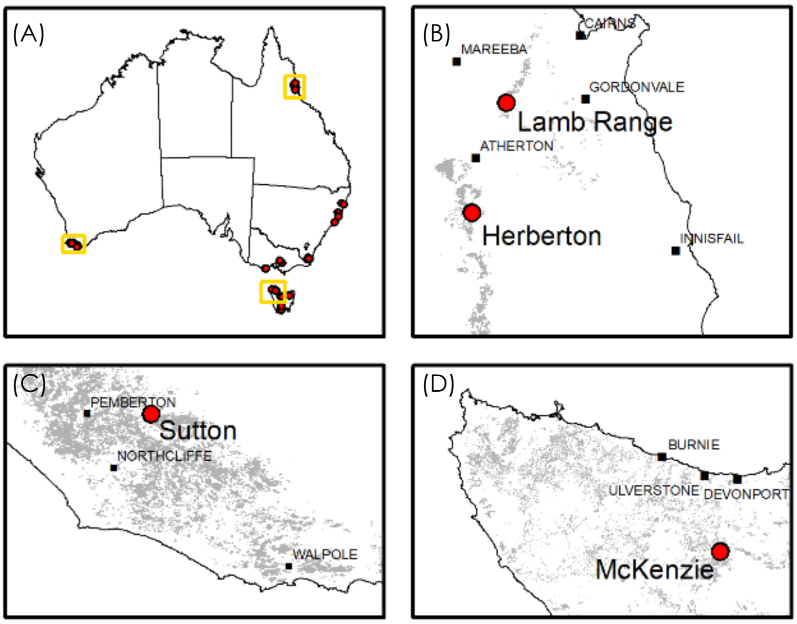


FIGURE 1: MAPS SHOWING 2016 FIRES. (A) THE LOCATION OF ALL AUSPLOTS (SMALL RED DOTS) AND THE REGIONS IN WHICH THE LOW SEVERITY FIRES OCCURRED IN 2016 (YELLOW RECTANGLES), (B-D) THE LOCATION OF THE FOUR AUSPLOTS THAT BURNED IN 2016 IN THEIR RESPECTIVE REGIONS, (B) QLD: NORTH QUEENSLAND, (C) WA:SOUTHWEST WESTERN AUSTRALIA, AND (C) HTAS: CENTRAL TASMANIA. NAMES OF THE BURNT AUSLPLOTS ARE GIVEN IN LARGE TYPE. THE GREY SHADED AREAS REPRESENT THE EXTENT OF TALL WET EUCALYPT FOREST IN THE REGION.

were extracted from the BOM Barra reanalysis project.[5] Conditions during the 2020 fires were estimated using daily linescan data and a weighted average of conditions measured by all weather stations within 100 km.[6] These conditions are outlined in tables 2 & 3.

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

TABLE 1: SUMMARY INFORMATION OF THE THREE TERN AUSPLOTS THAT BURNED BETWEEN OCTOBER 2014 AND FEBRUARY 2020, 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	Remeasure-ment Date
McKenzie	TAS	TAS North Slopes	TFA Future Reserve	*E. delegatensis*	3/3/2015	Low-Severity 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
Candelo	NSW	SE Corner	South East Forests NP	*E. fastigata*	24/11/2014	High-Severity Wildfire	1/2/2020	22/04/2021
Wog Way	NSW	SE Corner	South East Forests NP	*E. fastigata*	26/11/2014	High-Severity Wildfire	29-31/1/2020	16/4/2021
Waratah	NSW	SE Corner	South East Forests NP	*E. fastigata*	28/11/2014	Moderate-Severity	1/2/2020	15/4/2021
Newline	NSW	SE Corner	South East Forests NP	*E. fastigata*	25/11/2014	Low-Severity	29-30/1/2020	20/4/2021

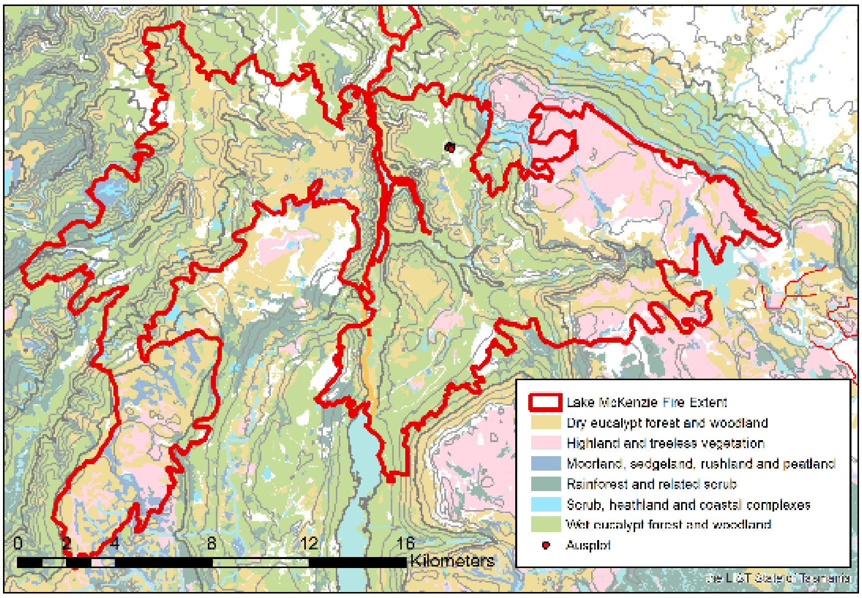


FIGURE 2: MAP SHOWING EXTENT OF THE LAKE MCKENZIE FIRE, THE LOCATION OF THE MCKENZIE AUSPLOT, AND THE DISTRIBUTION OF THE MAJOR NATIVE VEGETATION TYPES IN THE REGION. DATA SOURCES: TASMANIA FIRE SERVICE[3] AND TASVEG 3.0[7]

2016.[7] Though the fire garnered international headlines for its destruction of fire-intolerant ecosystems such as cushion plant, pencil pine, and king-billy pine,[8] 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.[9] 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

TABLE 2: SUMMARY OF MOST SEVERE WEATHER CONDITIONS ON THE DAY THAT EACH OF THE EIGHT PLOTS BURNED. TEMPERATURE (°C), RELATIVE HUMIDITY (%), WIND SPEED (KM/H), DORUGHT FACTOR, AND MCARTHUR'S FOREST FIRE DANGER INDEX ARE GIVEN.

Plot Name	State	Date of Fire	Temper-ature (°C)	Relative Humidity (%)	Wind Speed (km/h)	FFDI
McKenzie	TAS	24/1/2016	22.7	37.1	16.92	10
Lamb Range	QLD	28/10/2014	20.4	28	21.24	21
Herberton	QLD	13/8/2015	22	30	5.76	13
Sutton	WA	20/1/2017	26.4	36.9	11.52	11
Candelo	NSW	1/2/2020	36.6	37	15.5	29
Wog Way	NSW	29-31/1/2020	35	26	11.7	28
Waratah	NSW	1/2/2020	37.9	22	51.8	39
Newline	NSW	29-30/1/2020	32.4	17	11.2	20

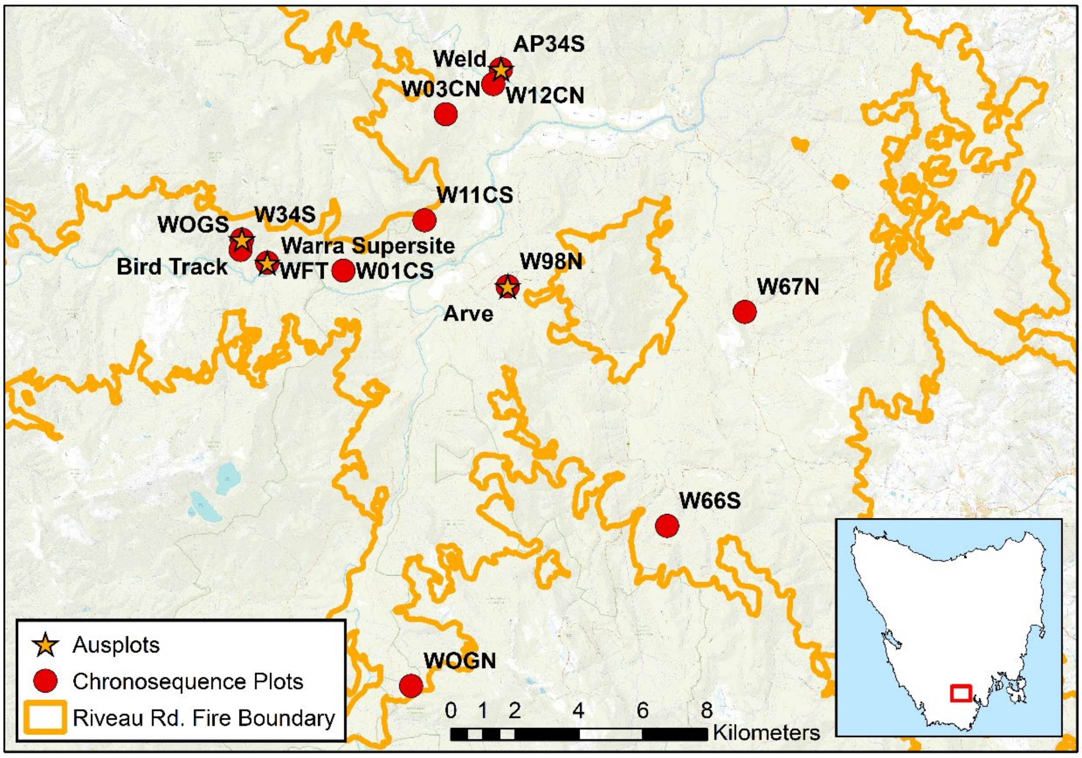


FIGURE 3: MAP OF THE LOCATION OF THE 4 AUSPLOTS (STARS) AND 12 CHRONOSEQUENCE PLOTS (CIRCLES) BURNED IN THE 2019 RIVEAUX RD FIRE

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.[10] 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.[11] 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 (AFAC). 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. The fire burned through forest dominated by *Eucalyptus regnans* and *E. obliqua* with both rainforest and broadleaf understoreys, both of which are non-flammable and fire sensitive. The area burnt included 12 Chronosequence plots and four Ausplots. The period in the second half of January, during which all but one of the plots burned, was marked by extremely variable fire weather, 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).

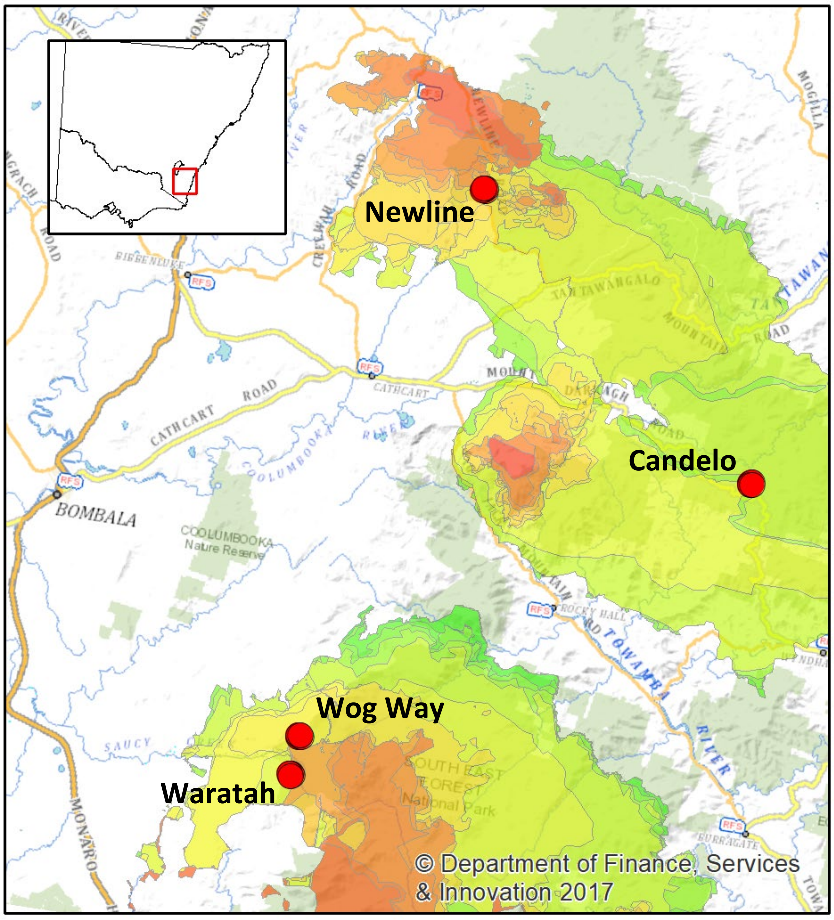


FIGURE 4; MAP OF FOUR PLOTS IN NEW SOUTH WALES THAT BURNED DURING THE 2020 FIRES. COLOUR GRADIENT OF POLYGONS REPRESENT FIRE PROGRESSION. RED POLYGON S BURNED ON 23 JAN 2021, YELLOW POLYGONS BURNED ON THE 31 JAN, AND GREEN POLYGONS BURNED ON 12 FEB.

The 2019-20 'Black Summer' bushfires across Australia made international headlines, burning over 30 million hectares and 18% of Australia's Eucalypt forests.[12] While the extreme fire behaviour experienced on New Year's Eve was particularly noteworthy,[13] these fires burned well into February and March. In late January/early February, two of these fires burned four of the five Ausplots in southern New South Wales. The Border Fire burned over 192,000 ha in Victoria and New South Wales between 31 Dec 2019 and 4 March 2020.[14] It burned two Ausplots in Southeast Forests National Park Southeast of Bombala: Wog Way and Waratah. The Creewah-Postaman's Track-Big Jack Mountain Fire complex burned over 42,000 ha northeast of Bombala during a similar time period, burning two more Ausplots in this area: Newline and Candelo (fig 4). These plots were dominated by *E. fastigata, E. viminalis, and E.* obliqua. Importantly, and unlike the other Ausplots that burned, there were very few non-flammable or fire sensitive trees in the elevated layer or mid-storey.[1] Site and fire overviews are given in table 1. We have not yet calculated the fire weather at the precise time that the plots burned, but we give an estimated range based on weather station records in table 2. Newline and Waratah burned at low-moderate severity, with canopies only partially scorched, whereas Candelo and Wog Way burned at high-severity, with full crown scorch and partial crown fires.

These fires presented us with an excellent opportunity to obtain fuel load, structure, and hazard measurements both directly before and after low- and high-severity fires. Not only would such measurements provide an estimate of

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-Developm ent 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

how much fuel is consumed in fires of varying severity, but such fuels data could be used to assess how quickly tall wet eucalypts forests recover from low- and high-severity fire. 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.

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.

OBJECTIVES

The main goal of this study is to obtain empirical measurements of fuel load, structure and hazard within the first two years 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 a range of 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 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

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.[15,] 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, [16,17] there is much debate over whether this is the true trajectory of flammability in these forests.[18,19,20] 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,[21] and as only the latter can be physically manipulated, the effect of fuel load and structure on fire behaviour, and the subsequent reduction in fuels, is extremely important to understand. Planned burning, the intentional use of low-severity fire, 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,[22,23,24] the effect of low severity fires on actual fuel loads has not been explicitly quantified, especially in wet forests where planned burning is less commonly practiced than in dry forest. Further, low-severity fires have historically been overlooked in wet forests, as high-severity fires are though to be the important disturbance type due to the serotinous nature of many eucalypts. But recent research indicates that low-severity fires could play a more important role that previously realised.[26]

RELATED PROJECTS

This study is building a large dataset of pre- and post-fire permanent plot measurements to complement existing studies on the fire regime of wet eucalypt forests.[25] As mentioned above it utilised infrastructure set up as part of the TERN forests Ausplots network,[26] and the Warra Chronosequence plots.[27] Such a dataset will allow for analyses such as the validation of fire behaviour models, analysis of the resilience wet forests to wildfire, and help understand how fire severity affects subsequent fire hazard. Data from this study has already added a valuable validation section to a study providing the first-ever explicit description of the fire regime of mature wet *Eucalyptus* forests across Australia.[26]

This project has also contributed a valuable high-resolution field-based validation 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 *Eucalyptus* forests.

RESEARCH QUESTIONS

This study plans to focus on three major research questions:

- What is the effect of low-, moderate-, and high-severity fires on fuel loads 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, November 2019 – January 2020, and in April 2021. The methodology for the fuel surveys of both the Ausplots and the Chronosequence plots was derived from NASA-funded fuel surveys.[28]

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 5a). From February-July 2016, we performed fuel surveys along three 30m transects at each Chronosequence plot (fig 5b). We used the transects to measure surface, near surface, and elevated fuel load (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.[29] 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.[30]

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 and a subsample of at least 350g of each fuel category from each quadrat. We then oven-dried these samples 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.

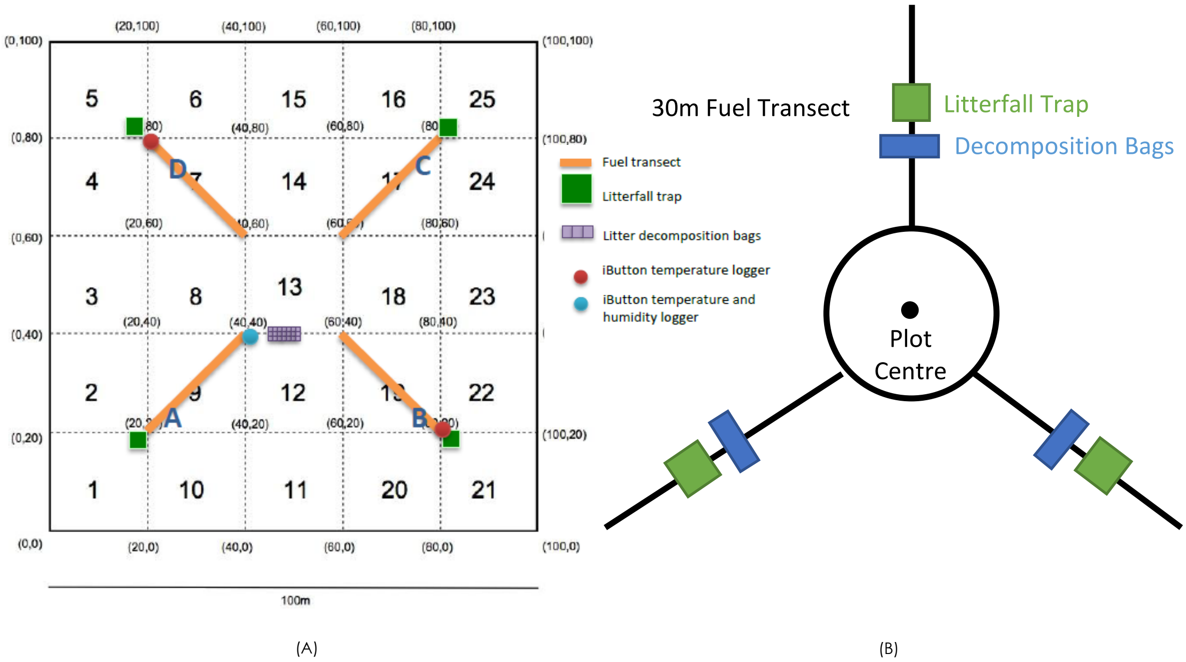


FIGURE 5: DIAGRAM OF THE LOCATION OF THE FUEL TRANSECTS, LITTERFALL TRAPS, AND DECOMPOSITION BAGS IN (A) THE AUSPLOTS AND (B) THE CHRONOSEQUENCE PLOTS

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[31,32]: (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 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.[33,34]

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, all ground ferns, regardless of height, were considered part of the near-surface layer, and not measured at this stage. In all

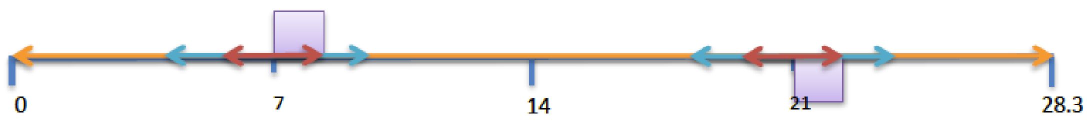


FIGURE 6: EXTENT OF WOODY FUEL COUNTS AND FINE FUEL QUADRTATS[2]

plots, we defined any plant, other than tree ferns, that had a DBH >10cm 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, 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.[35,36]

REMEASUREMENT OF BURNT PLOTS

In November of 2016 and 2017, November 2019 - January 2020, and most recently in April 2021, we returned to the 12 Ausplots and 12 Chronosequence plots that had burnt after the initial fuel surveys. We mostly 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

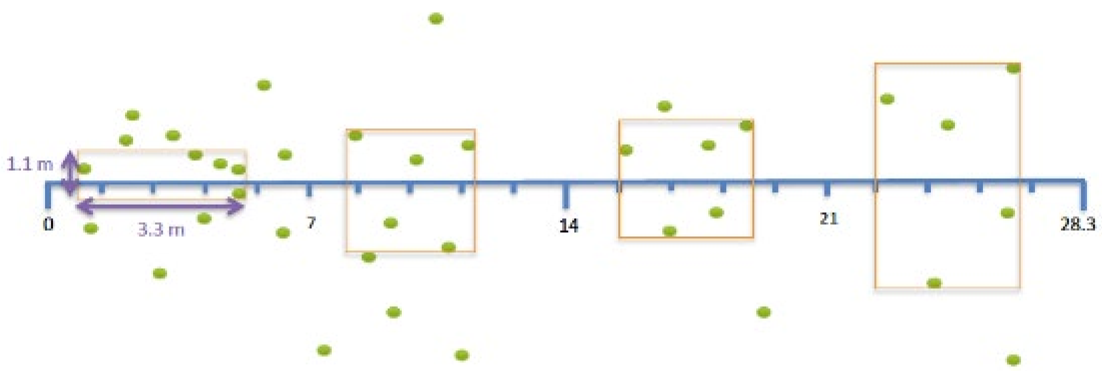


FIGURE 7: DIAGRAM OF CHOICE OF SHRUBS AND MEASUREMENT OF SURROUNDING RECTANGLE.[2]

transect in 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.

Elevated Fuels

We made all the same measurements in the elevated fuels as in the original fuel surveys, measuring 20 live plants on each transect. For our analysis we subdivided these plants into two groups: regenerating (released from seed or spore after the fire) plants and resprouting plants. We also took several 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 for which a stem diameter at breast height was not present. 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 then used this data to estimate the standing biomass of regenerating, resprouting, and dead plants in the elevated layer. We estimated the biomass of resprouting and regenerating plants using the aforementioned equations, and for the dead plants we used similar allometric equations predicting biomass partitioning to calculate the biomass of branches without foliage.[37]

Fire Intensity and Severity

In the Ausplots, to measure severity of the fires, we measured the height of charring on each overtorey tree (except those with fibrous bark) within the 20 x 20m subplot containing each transect (fig 4a). This measure is a good correlate for flame height and hence fire intensity.[38] In New South Wales and Tasmania we also estimated overstorey mortality, measuring the basal area of live and dead trees in these four subplots. In New South Wales, where the overstorey consisted almost exclusively of resprouters, we also gave each tree a qualitative score based on resprouting intensity:

1-minimal resprouting with an in-tact canopy
2-substantial epicormic resprouting with an in-tact canopy
3-complete canopy scorch with epicormic and branch resprouting
4-epicormic resprouting with dead branches
5-basal/lower stem epicormic resprouting only

We then compared the diameter of trees in each resprouting class as a measure of fire severity.

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 1.8m 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.[39] 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. Meanwhile high-severity fires consumed most of the elevated layer but resulted in a pulse of regenerating biomass. In all cases, the thinning of elevated fuels will likely dry out the understorey, potentially leaving these forests vulnerable to future fires.

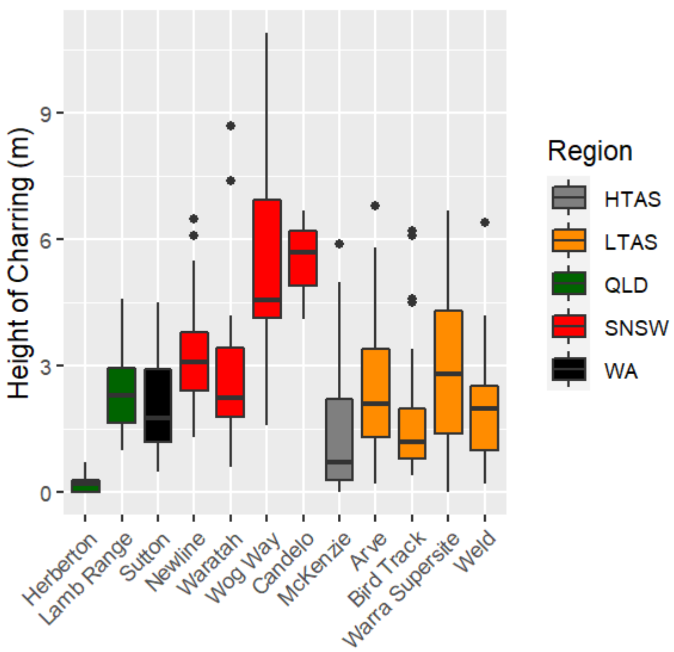


FIGURE 8: FLAME HEIGHT EXPEREINCED AT EACH OF THE 12 BURNT AUSPLOTS, AS MEASURED BY CHARRING ON NON-STRINGY BARK OVERSTOREY TREES

FIRE INTENSITY AND SEVERITY

Intensity

Fire intensity, as measured by charring on trees, a correlate for flame height, was highly variable across the burnt plots (fig 8). As expected, the most intense fires were experienced at the SNSW plots during the 2020 bushfires (specifically in Candelo and Wog Way). However, flame heights in the two SNSW Ausplots that burned at low-moderate severity were similar to flame heights experienced in LTAS in the 2019 Riveaux Rd, which was a mostly low-moderate severity fire. This highlights the prevalence of low-intensity wildfire in wet *Eucalyptus* forests even during catastrophic wildfires.[40,26] Also of note is that the lowest intensity wildfires (at McKenzie, Bird Track, and Weld) had similar fire intensities to the planned burns (at Herberton, Lamb Range, and Sutton), with flame heights mostly less than 3m.

Severity of Fires In Southern New South Wales

Due to the large amount of variation in fire severity experienced by the Ausplots in SNSW, and due to the exclusive dominance of resprouting eucalypts in the mid-storey and emergent canopy, we measured the fire severity in each of the subplots containing transects, using the diameter distribution of trees in each of 5 resprouting intensity classes, and the percent overstorey mortality as severity measures (fig 9). These results confirmed our initial observations of fire severity, namely that Wog Way and Candelo burned at a high severity, as evidenced by the large amount of mortality in Candelo (fig 9a), and the number of large trees (> 50cm DBH) that experienced either complete canopy scorch (resprouting class 3) or canopy damage and branch loss (resprouting class 4; fig 9b).

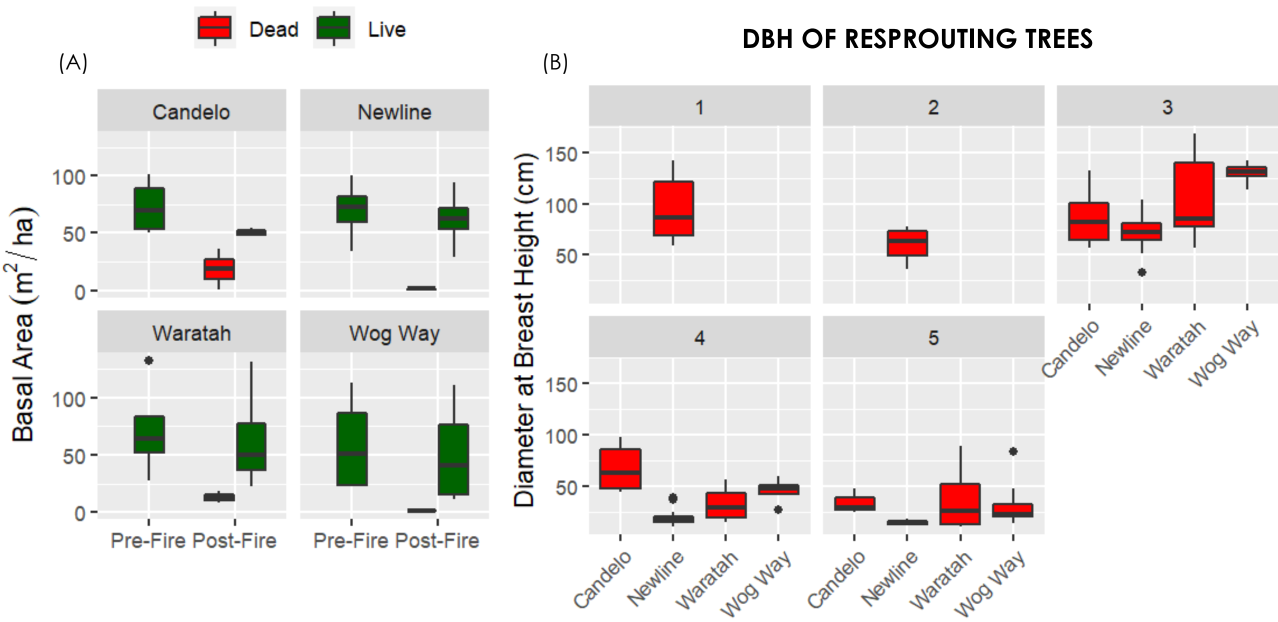


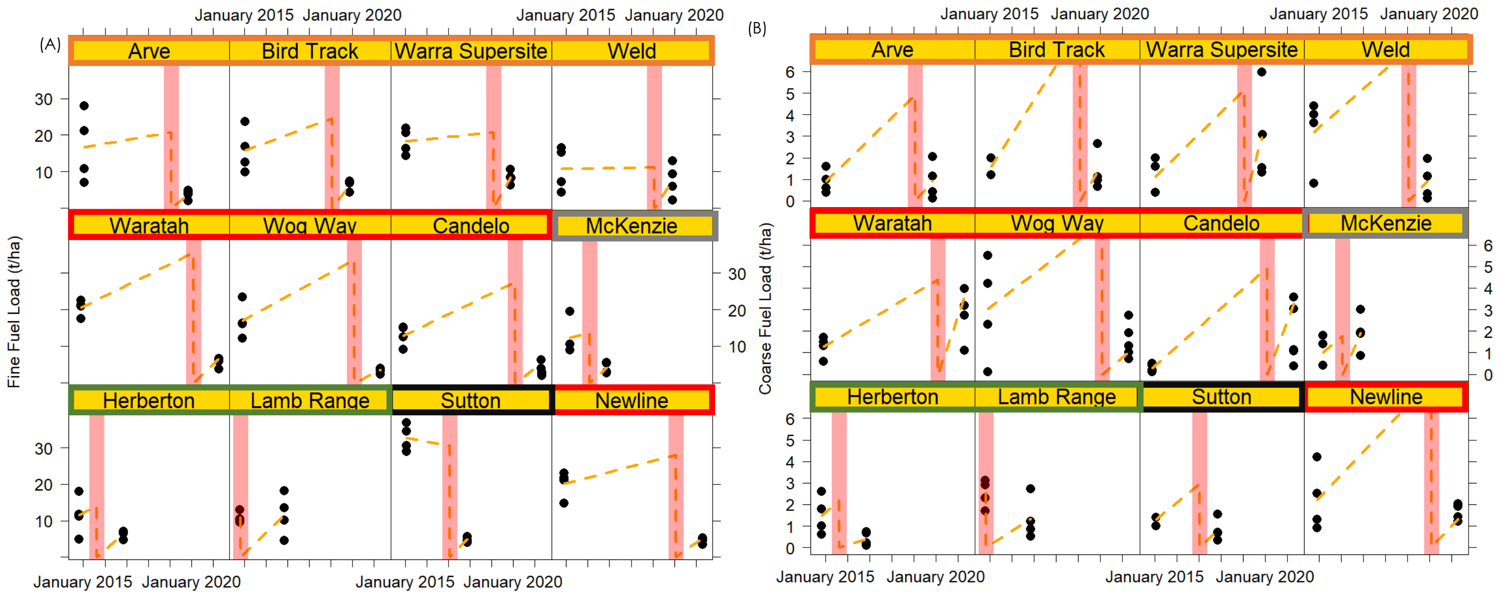
FIGURE 9: FIRE SEVERITY AT THE FOUR SNSW PLOTS. (A) DISPLAYS THE BASAL AREA OF LIVE TREES (>10CM DBH) BEFORE THE FIRE AND OF BOTH LIVE AND DEAD TREES AFTER THE FIRE IN FOUR SUBPLOTS FOR EACH AUSPLOT. (B) DISPLAYS THE DIAMETER DISTRIBUTION OF LIVING OVERSTOREY TREES IN EACH OF FIVE RESPROUTING CLASSES, WITH 1 REPRESENTING TREES MOSTLY UNAFFECTED BY FIRE AND 5 REPRESENTING TREES NEARLY KILLED BY FIRE (SEE METHODS).

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 low-moderate intensity fire. All Ausplots (except in SNSW) and Chronosequence plots had accumulated roughly 5 t/ha of surface fine fuels within the first year after a fire (figs 10a, 11). 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 likely occurred due to the death, but lack of consumption, of the less flammable understorey and mid-storey trees and shrubs. 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 10a, 11) Given the primary importance of fine fuels in driving fire behaviour, this is potentially an important result regarding the effectiveness of planned burning in different climates and stand development stages in wet *Eucalyptus* forests.

In contrast, in SNSW, where the fires were higher severity, and where the mid-storey was dominated by much more flammable eucalypts, less than 5 t/ha of fuels had re-accumulated in over a year. All sites had a relatively high re-accumulation of coarse fuels (fig 10b).



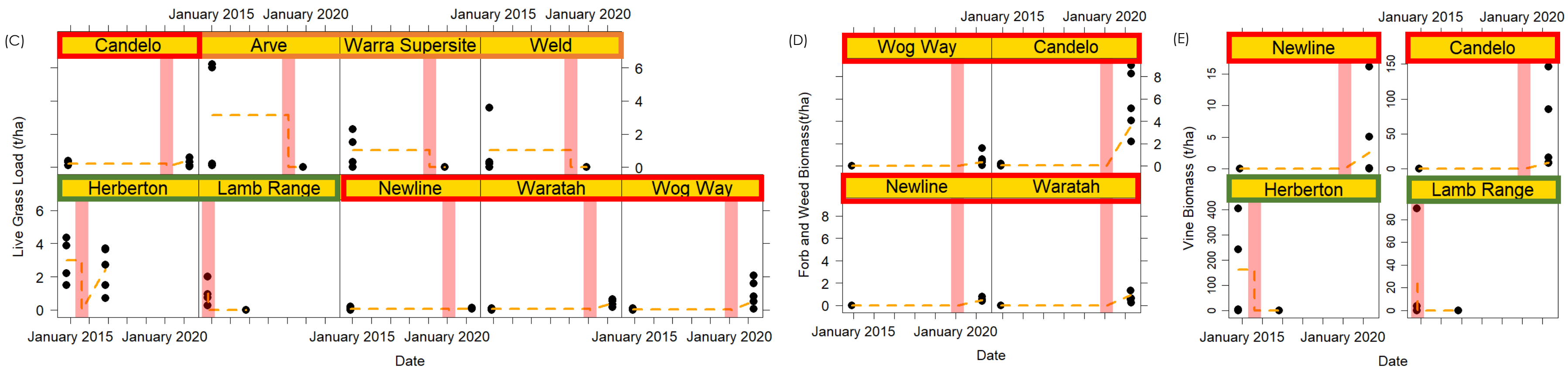


FIGURE 10: TIMELINE OF SURFACE NEAR-SURFACE FUEL LOADS (IN TONNES PER HECTARE) AT EACH AUSPLOT. (A) DEPICTS FINE FUELS, (B) COARSE WOODY FUELS (0.6-2.5 CM DIAMETER, 1 HOUR DRYING CLASS) (C) LIVE GRASS, (D) FORBS AND WEEDS, AND (E) LIVE VINES. THE BLACK DOTS REPRESENT INDIVIDUAL QUADRATS, AND THE ORANGE DOTTED 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. THE COLOR BORDERING THE PANEL REPRESENTS THE REGION OF THE GIVEN AUSPLOT: ORANGE-LTAS; GREY-HTAS; RED-SNSW; BLACK-WA; AND GREEN-QLD.

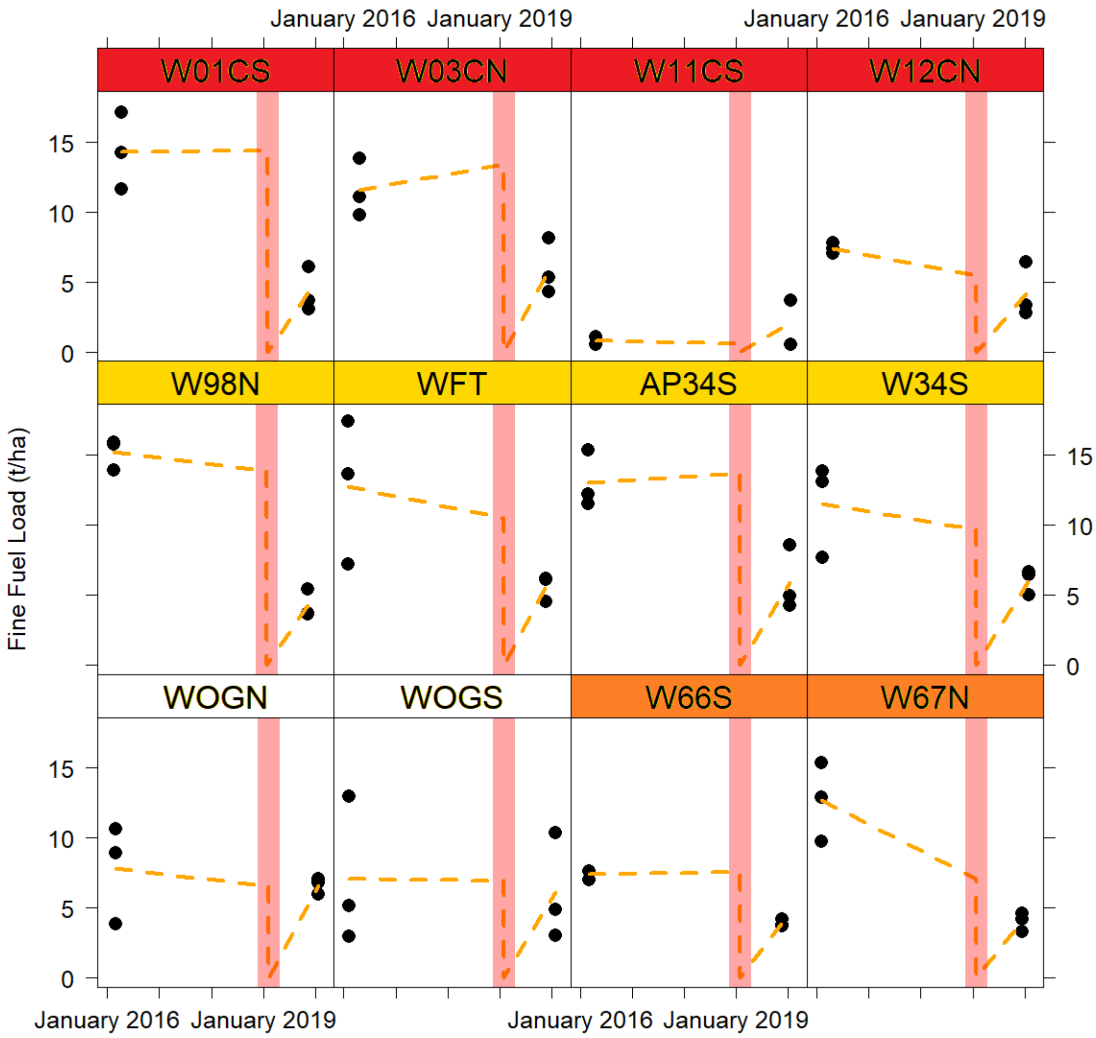


FIGURE 11: TIMELINE OF SURFACE FINE FUEL LOADS (IN TONNES PER HECTARE) AT THE CHRONOSEQUENCE PLOTS. THE BLACK DOTS REPRESENT INDIVIDUAL QUADRATS, AND THE ORANGE DOTTEDD LINE REPRTESENTS THE ESTIMATED FUEL ACCUMULATION PATTERN. FUEL ACCUMULATION WAS INFERRED FROM PREVIOUSLY MEASURED RATES (SEE METHODS) 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 (GREY), EARLY-MATURE (YELLOW), SPAR (ORANGE), AND SAPLING (RED)

Live Near-Surface Fuels

The trend among grasses is less consistent (fig 8c). Nine sites had significant grass presence before or after the fires. In Herberton, grasses seem to have quickly regrown: the site was being colonised by the highly flammable *Imperata cylindrica*[41], but in Lamb Range (QLD), Arve, Warra Supersite, and Weld (TAS), grasses (such as *I. cylindrica* in QLD and *Gahnia grandis* in TAS) did not start growing back in the 1-2 years post fire. Meanwhile in SNSW, a huge amount of biomass (more than 10 t/ha in some transects) was regenerating in the near-surface layer (including grasses, vines, and forbs and weeds, figs 8c-e).

ELEVATED FUELS

Perhaps the most consistent effect of the low-moderate severity fires across all plots, once again except in SNSW, 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 through resprouting. This is apparent in the Ausplots through a reduction of the fuel load and bulk density of fine fuels in the elevated layer among regenerating, resprouting, and dead plants (fig 12), except for tree ferns. It appears the effect of these low-moderate severity wildfires was to transfer fuels from the elevated layer to the surface layer through defoliation of the understorey.

Meanwhile in SNSW, where fire-tolerant resprouting eucalypts were much more prominent in the understorey and mid-storey, and where fire intensity was generally higher, a larger portion of the elevated fuels seems to have been consumed by the fire, with only a small proportion remaining as standing dead trees and shrubs. However, this elevated fuel load has been replaced by regenerating and resprouting biomass, and these fuels have a higher bulk density than before the fire. Given the importance of elevated fuels in driving extreme fire behaviour,[26] this suggests that these forests could be vulnerable to repeated high-intensity fires if the understorey dries out adequately during a subsequent drought. Also of interest in these plots is the large amount of regeneration in both eucalypts and other seedlings (mostly *Acacia melanoxylon*) in the three plots with the highest fire severity (Waratah, Wog Way, and Candelo; fig 9b). Interestingly, the site with the most canopy mortality (Candelo; fig 9a), has the least *Eucalyptus* regeneration of the 3, which contradicts theory about *Eucalyptus* needing canopy openings to regenerate. The mechanisms behind this will need further exploration.

In the Chronosequence plots, the death of the understorey is apparent through the hazard assessment of the elevated layer (fig 13), 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 14), 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.

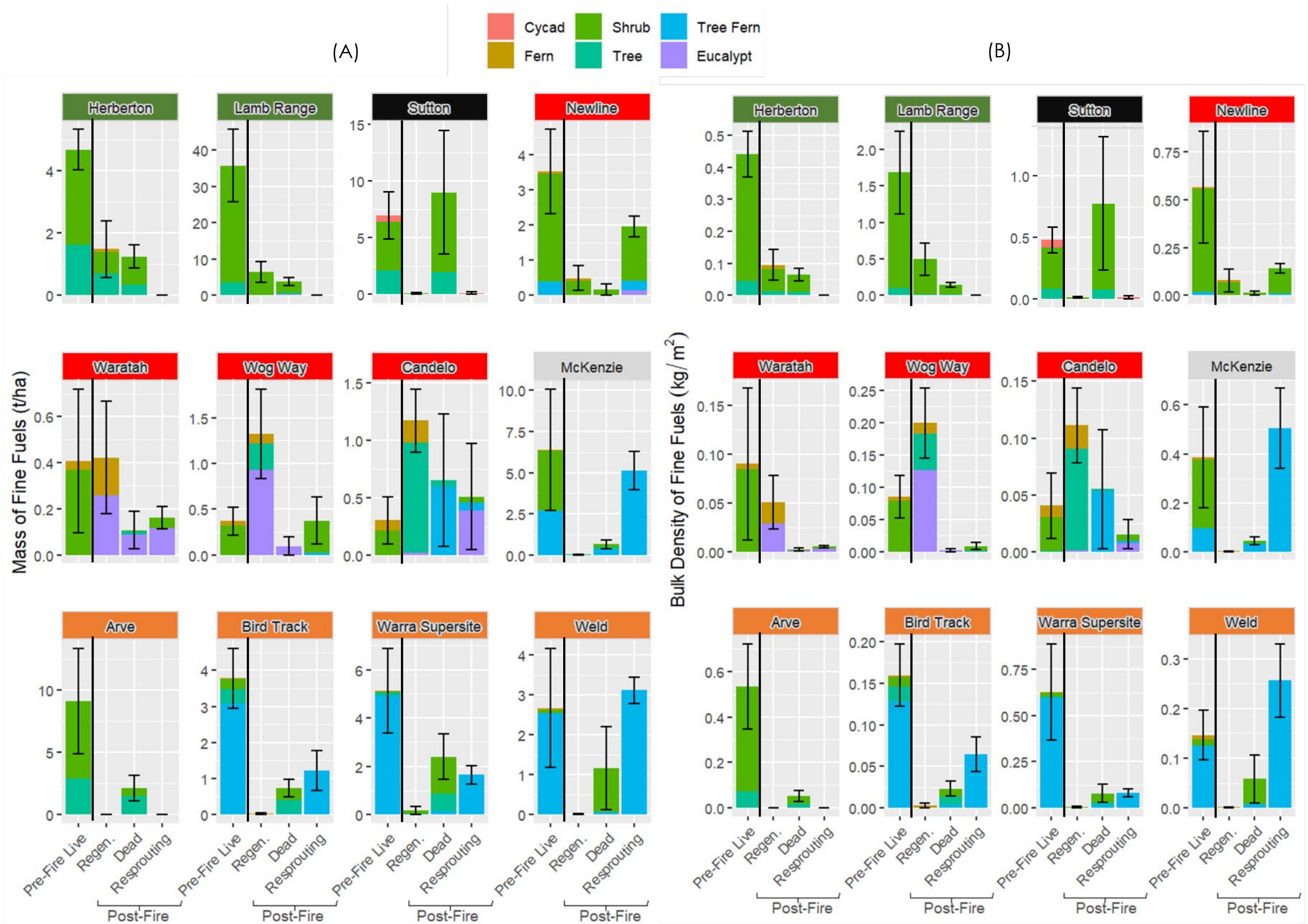


FIGURE 12: (A) STACKED BAR PLOT DISPLAYING ESTIMATED BIOMASS IN TONNES PER HECTARE OF PRE-FIRE LIVE FINE FUELS IN PLANTS IN THE ELEVATED LAYER (LEFT SIDE OF BLACK LINE IN EACH GRAPH), AND OF POST-FIRE REGENERATING, DEAD, AND RESPROUTING PLANTS IN THE ELEVATED LAYER (RIGHT SIDE OF BLACK LINE) AT EACH SITE. COLORING OF BARS REPRESENTS THE PROPORTION OF THE FUELS REPRESENTED BY EACH OF SIX PLANT GROWTH FORMS AS INDICATED. LIVE FINE FUELS ARE DEFINED AS ALL FOLIAGE AND TWIGS <0.6CM DIAMETER. (B) ESTIMATED BULK DENSITY OF THE SAME FUEL CATEGORIES IN (A) IN THE ELEVATED LAYER BASED ON THE AVERAGE PLANT HEIGHT IN EACH SUBPLOT. ERROR BARS REPRESENT ONE STANDARD ERROR. PLOT NAMES ARE SHADED BASED ON REGION: ORANGE-LTAS; GREY-HTAS; RED-SNSW; BLACK-WA; AND GREEN-QLD. NOTE EACH GRAPH HAS A DIFFERENT SCALE ON THE Y-AXIS.

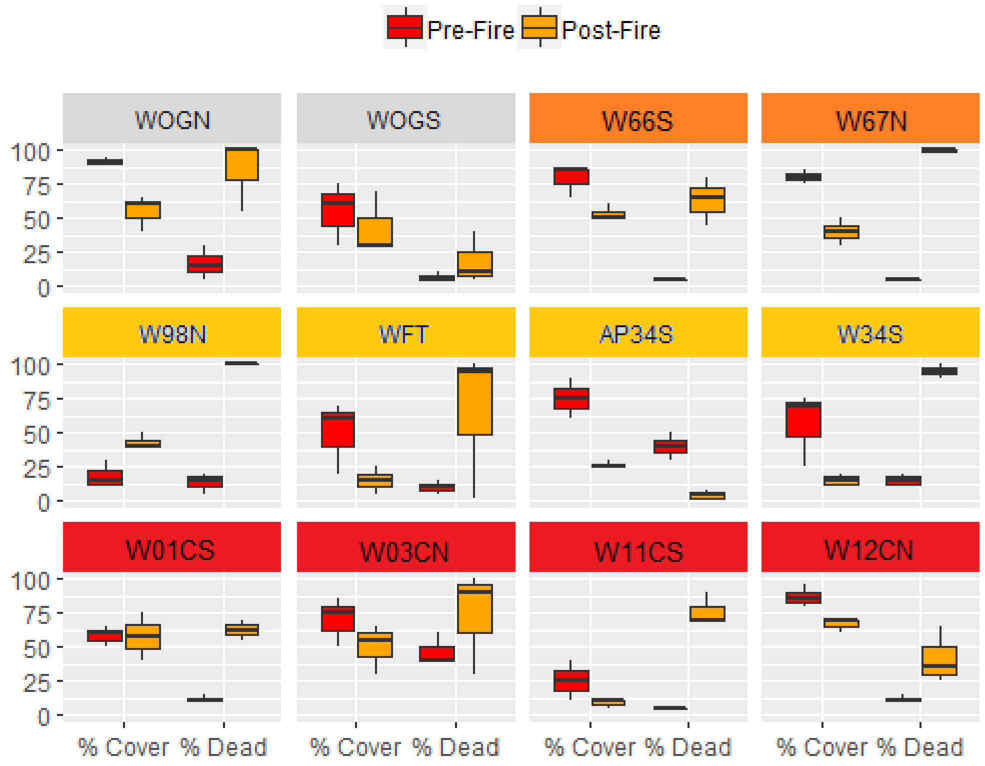


FIGURE 13: ESTIMATED PERCENT DEAD FUELS AND PERCENT COVER IN THE ELEVATED LAYER BEFORE AND AFTER THE FIRE IN THE CHRONOSEQUENCE PLOTS. PANEL COLOUR REPRESENTS STAND DEVELOPMENT STAGE: LATE-MATURE (GREY), EARLY-MATURE (YELLOW), SPAR (ORANGE), AND SAPLING (RED)

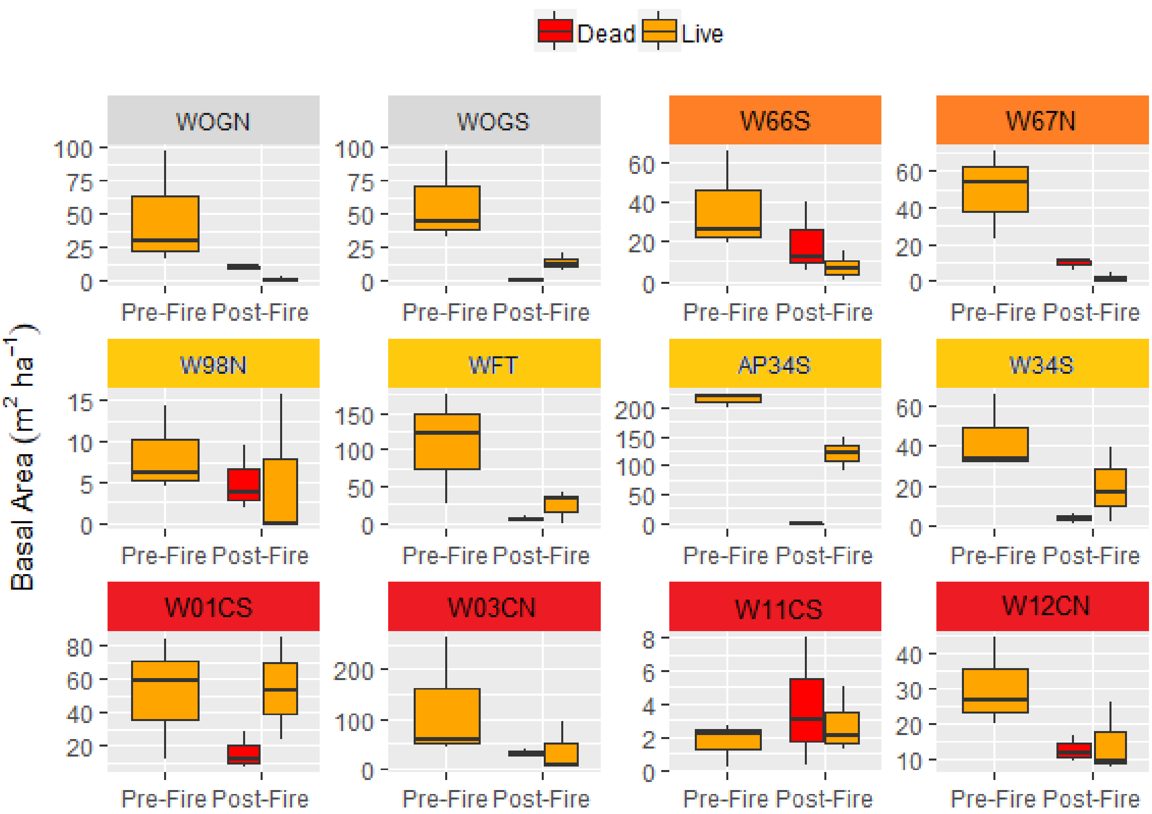


FIGURE 14: BASAL AREA PER HECTARE OF LIVE (ORANGE BOXES) AND DEAD (RED BOXES) STANDING PLANTS IN THE ELEVATED LAYER BEFORE AND AFTER THE FIRE IN THE CHRONOSEQUENCE PLOTS. PANEL COLOUR REPRESENTS STAND DEVELOPMENT STAGE: LATE-MATURE (GREY), EARLY-MATURE (YELLOW), SPAR (ORANGE), AND SAPLING (RED)

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.[42][43] 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.[44] Such fires in quick succession have been shown to be catastrophic in obligate-seeder dominated wet forests, especially those in the sapling stage,[45] and could be problematic in resprouter dominated forests as well.[46] 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.

This data, in combination with data generated from a 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.

Lastly, this report represents the culmination of three different quick-response projects to compile a detailed database of pre- and post-fire vegetation and fuels data. This database will allow for the answering of questions such as how accurate are our fire behaviour models, how do wet eucalypt forests respond to low- and high-severity wildfires, and how vulnerable are resprouter forests to successive fires. These are all fundamental questions relating to the fire ecology and fire danger in tall wet eucalypt forests that need answering. This dataset will form the basis for funding applications for future large-scale projects to answer these questions.

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