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# INFORMING POST-FIRE RECOVERY PLANNING OF NORTHERN NSW RAINFORESTS

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Cover: Burnt and collapsed veteran *Nothofagus moorei* tree Werrikimbe National Park northern NSW September 2020 with field team member Irene Xiao (tree was burnt on November 9th 2019). Source: Ross Peacock

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# ACKNOWLEDGMENTS

A team of NSW agency staff and volunteers supported the completion of this study, which is based on the re-measurement of permanent rainforest growth plots that were originally established by the former Forestry Commission of NSW in the late 1950's. Volunteers supporting the remote area field work campaign included Nishat Anjum, John Allen, Emeritus Prof. Ross Bradstock, Bill Chapman, Assoc. Prof. Doland Nichols, Neil Pash, Amy Smart, Amelia Thomas, Rebeca Violante and Irene Xiao.

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The research was conducted using Scientific Licence SL101239 from the NSW Department of Planning, Industry and Environment. Volunteers were supported by the NSW National Parks and Wildlife Service volunteer program.

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Field work costs were supported by the Bushfire and Natural Hazards CRC and NSW National Parks and Wildlife Service (Tricia Waters).

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John Bates, Nicklaus Mahony and Andrew Yin of the Bushfire and Natural Hazards CRC provided the project management support enabling the research to be presented and available to agencies managing the 2019/20 wildfire recovery planning process. Staff at Macquarie University Department of Natural Sciences and the Research Services office managed the contractual and financial arrangements.

# EXECUTIVE SUMMARY

In historic times rainforests have comprised less than 2% of the total forested area of NSW (Baur 1987) yet they have played a pivotal role in the states early timber industry, and the development of conservation policy, and are the only plant community in NSW to have been included in the name of a World Heritage property. The Gondwanan rainforests evolved in an environment of dependable rainfall and low fire frequency. They have persisted through multiple climate oscillations and glacial/inter-glacial cycles in refugia scattered through the Great Escarpment uplift landform. They now represent a collection of relictual species whose origins can be traced to the Eocene Epoch 55-37 million years ago when cool temperate taxa such as *Nothofagus* first appears in the fossil record.

In northern New South Wales, temperate rainforests are typically considered to be vulnerable to climate-change related natural hazards such as extended spring droughts and wildfires. Numerous reviews predict that extreme climatic events are likely to increase in frequency and/or intensity in coming decades (CSIRO 2019, 2020) and that wildfires will become larger, more intense, and more frequent. The vulnerability of temperate rainforests to fire is assumed to be the result of their limited intrinsic post-fire regenerative capacity, their susceptibility to canopy scorch and bark damage, and extrinsic factors such as their landscape position as patches within extensive areas of elevated fuel hazard in wet sclerophyll forest and woodland plant communities. The impacts of wildfires on temperate rainforests are heightened because wildfires are naturally infrequent, the vegetation is poorly adapted to fire, and fuel biomass is abundant and contiguous in the surrounding landscape.

During the 2019/20 wildfire season, 18.1% of the extent of NSW's rainforest vegetation classes experienced either low, moderate, high, or extreme severity wildfire, a scale un-anticipated in earlier land management risk planning. While the proportion of each class varied, the greatest impacts occurred in Dry Rainforest and Northern Warm Temperate Rainforest. Across the Gondwana Rainforest of Australia World Heritage property (Gondwana Rainforests), 16 of the 28 reserves in the NSW section saw some fire impacts. This resulted in 8.6% of the 112,145 ha of rainforest in these reserves experiencing either low, moderate, high, or extreme severity wildfire. The extent of the fire impacts was greatest in the Hastings-Macleay, New England, and Washpool-Gibraltar Range sections of the Gondwana Rainforests. The focus of the current study is the Hastings-Macleay section.

The 2019/20 wildfire season coincided with the lowest annual rainfall recorded in the Hastings-Macleay study area since local records commenced in 1959. Soil moisture deficits in rainforest were at their lowest recorded levels at the end of an extended spring drought in northern NSW. An analysis using data from a decade of soil moisture monitoring indicated that when soil moisture in rainforest reached 10-20%, the rainforests become susceptible to fuel ignition and sustaining a wildfire.

In November 2019 multiple ignitions and running wildfires were occurring across northern NSW, and fire-fighting resources were prioritised to life and property protection. On November 9th 2019, an unprecedented seventeen wildfires were at Emergency Warning level on the same day in NSW, fire behaviour was erratic and rainforests were igniting and sustaining running fires. The wildfires impacted directly on long-term research plots established in 1959 in Werrikimbe and Willi National Parks in landscapes with extensive localised climate monitoring equipment. Resources were rapidly deployed within weeks of the wildfire impacting the research infrastructure to capture key elements of fire behaviour and commence post-fire assessments. With the financial support of the Bushfire and Natural Hazards CRC and NSW NPWS, citizen science volunteers began to measure the impacts of the wildfires and describe the recovery trajectory of the rainforest stands within the parks.

The long-term research plots provide a baseline to understanding pre-fire rainforest stand dynamics and condition. The 60 years of accumulated data highlighted the high biomass, slow growth rates, and highly episodic nature of tree regeneration in these rainforests. Annualized tree mortality was less than 1%, and canopy dieback was associated with previous selective harvesting in the 1960s. Fine fuel biomass is low and inputs are strongly seasonal. Basal fire scars were present on trees across the stands surveyed prior to the 2019/20 wildfire season, indicating past wildfires had occurred in these rainforests during the past century, and it appears the majority of established trees were resilient to their effects. Evidence from char heights indicates the predominant fire behaviour experienced by the larger rainforest trees is low-intensity litter fires that progress slowly through the rainforest stands. This was corroborated in discussions with fire managers who had witnessed fires across multiple northern NSW rainforest reserves. Evidence from archival fire reporting and mapping suggests that the typical fire season in the 1950s peaked in November and now peaks two months earlier. These rainforests are approaching the driest months in early spring when lightning ignitions are also at their seasonal maximum.

Wildfires entered rainforest from front or flank spread leading to attrition of trees on rainforest margins. Monitoring dominant trees for 12 years in smaller rainforest stands demonstrated that they can tolerate multiple fires until their structural integrity weakens and fails. In 2019/20 ember attack was widespread in rainforest, but generally led to the ignition of small, localised areas (<100 m$^2$) or of individual trees. Mortality rates associated with the wildfires were 20-30% across all tree species, with the proportion increasing with the severity of the wildfire event. This figure may prove to be an underestimate as lagged tree mortality effects from wildfires have been reported elsewhere for rainforests. The majority of burnt trees regenerated with basal coppicing. Seedling regeneration of tree species was infrequent due to the lack of a soil or canopy seed bank. Coppicing was more abundant where fire severity was low. Large trees with well-developed buttress hollows and scars were more likely to ignite due to the accumulation of dry wood and fuel at their base compared to smaller trees. Larger, older trees that had more pre-existing fire scars were more likely to die and collapse after burning. This is potentially an age effect where older and larger (diameter and height) trees have been subjected to more fire-induced wounds and hollows.

The temperate rainforests of northern NSW have been subject to wildfires in the past, and have a level of resilience to them. However, the susceptibility of the canopy dominant rainforest trees to basal wounding and collapse is a concern due to the longevity and age of these trees, their role in maintaining the rainforest microclimate, and their importance as habitat to a very diverse cargo of epiphytic bryophytes. Options to manage wildfire risk using conventional zoning and fuel hazard management may be limited. Fuel hazard was not particularly high during the 2019/20 wildfire season in the Hastings-Macleay section of Gondwana Rainforests, with most areas burnt in 2019 also having been burnt in 2013. Regardless, landscape-level fuel hazard management will not address the risk of individual mature rainforest tree ignition during conditions of significant ember attack when rainforest fine fuel biomass is naturally low.

A range of proposals are made to improve the knowledge base to better inform the spatially explicit wildfire risk assessment process trialled following the 2019/20 wildfire season. The central recommendation is the scoping of a systematic Monitoring, Evaluation and Reporting (MER) system for the Gondwana Rainforests of Australia World Heritage property (Gondwana Rainforests) that focuses on establishing a baseline to track trends in the nominated World Heritage outstanding universal values or criteria. The system will require an integrated remote sensing and ground-based plot monitoring approach stratified by rainforest type and location. The monitoring plots established for this study can be readily integrated into the proposed MER system, and can be used to test the significance of ongoing or lagged tree mortality and to validate models of post-wildfire tree mortality and regeneration.

The current study has informed post-fire recovery planning by assessing the significance of the impacts of the 2019/20 wildfire season on rainforest stand structure, composition, tree mortality, and regeneration strategies. While the field measurements were in progress, recovery planning workshops hosted by the Commonwealth and NSW governments were attended and preliminary results were provided. The availability of existing long-term rainforest monitoring experiments dating from the 1950s, sections of which were burnt in November 2019, was critical to providing preliminary results within months of the fire event (Peacock 2020) to inform post-fire recovery planning. This outcome alone underscores the critical role long-term ecological monitoring systems have in rapidly supporting land managers information needs when responding to widespread natural hazards such as landscape-scale wildfires.

# BACKGROUND

## GONDWANA RAINFORESTS OF AUSTRALIA WORLD HERITAGE AREA

The Gondwana Rainforests is a serial property consisting of numerous discontinuous reserves along the Great Escarpment of north-eastern New South Wales and south-eastern Queensland. These areas are of exceptionally high conservation value, with more than 200 rare or threatened plant and animal species. The Gondwana Rainforests satisfy three World Heritage criteria (viii, ix and x, Cavanaugh et al. 2010, Hunter 2004), relating to the unique biota and landforms across its 42 separate areas. The Gondwana Rainforests provides the major refugia for the remaining Gondwanan rainforest flora and fauna within the region, and its spectacular landforms are outstanding examples of ongoing geological processes (Adam 2017).

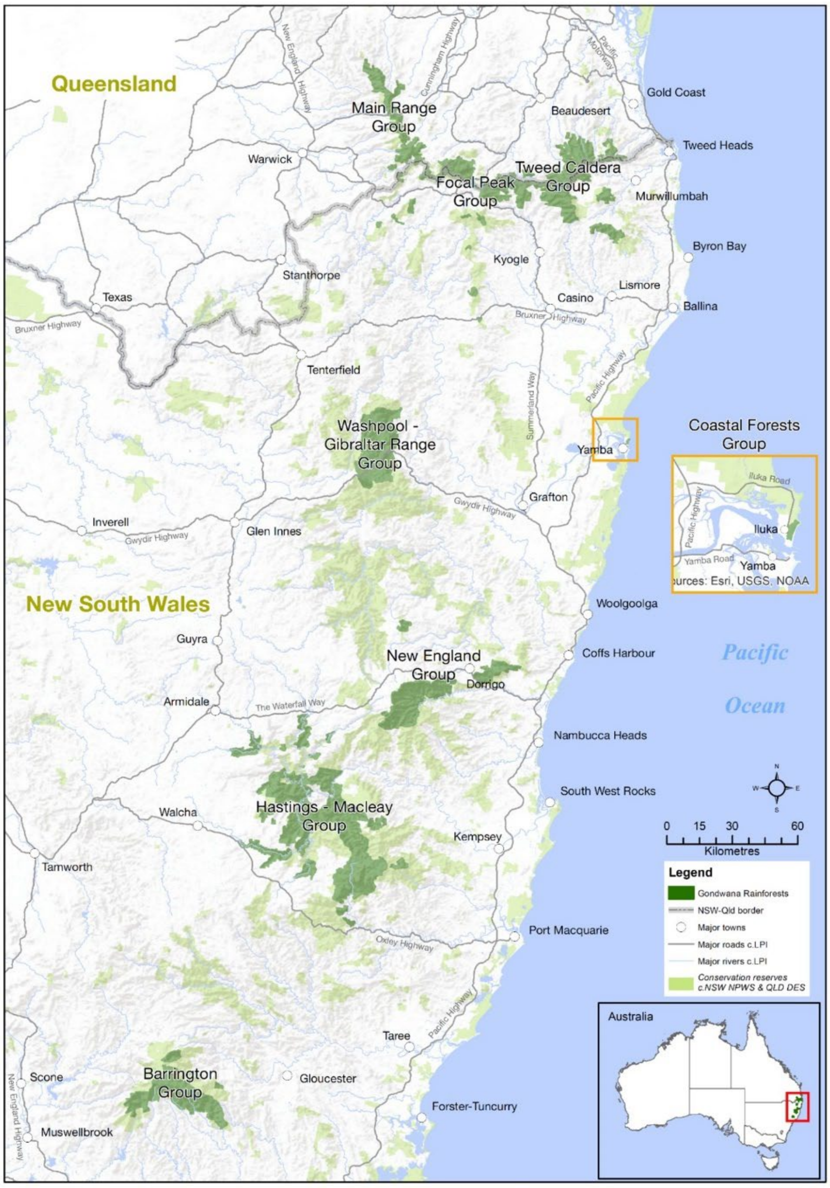

FIGURE 1: THE BOUNDARIES AND EXTENT OF THE GONDWANA RAINFORESTS OF AUSTRALIA WORLD HERITAGE AREA IN THE NEW ENGLAND AND HASTINGS-MACLEAY GROUP. THE FOCUS OF THE STUDY AREA IS THE HASTINGS-MACLEAY GROUP (YELLOW). SOURCE NSW DEPARTMENT OF PLANNING, INDUSTRY AND ENVIRONMENT (2020C)

The Gondwana Rainforests protects the most extensive areas of subtropical rainforest in the world, large areas of warm temperate rainforest and nearly all of the Antarctic beech (*Nothofagus moorei*) cool temperate rainforest in existence. The reserve consists of ancient vegetation and plant lineages that play a significant role in biodiversity conservation and evolutionary history of the Gondwana rainforests. The current study is focused on the Hastings-Macleay Group of the Gondwana World Heritage property (yellow in Figure 1) within the upper reaches of the Forbes and Wilson River catchments north-west of Port Macquarie. The vegetation of the study area is *Nothofagus moorei – Ceratopetalum apetalum* sub-alliance, cool temperate rainforest (Floyd 1990) or microphyll fern forest following the national classification (Webb 1959).

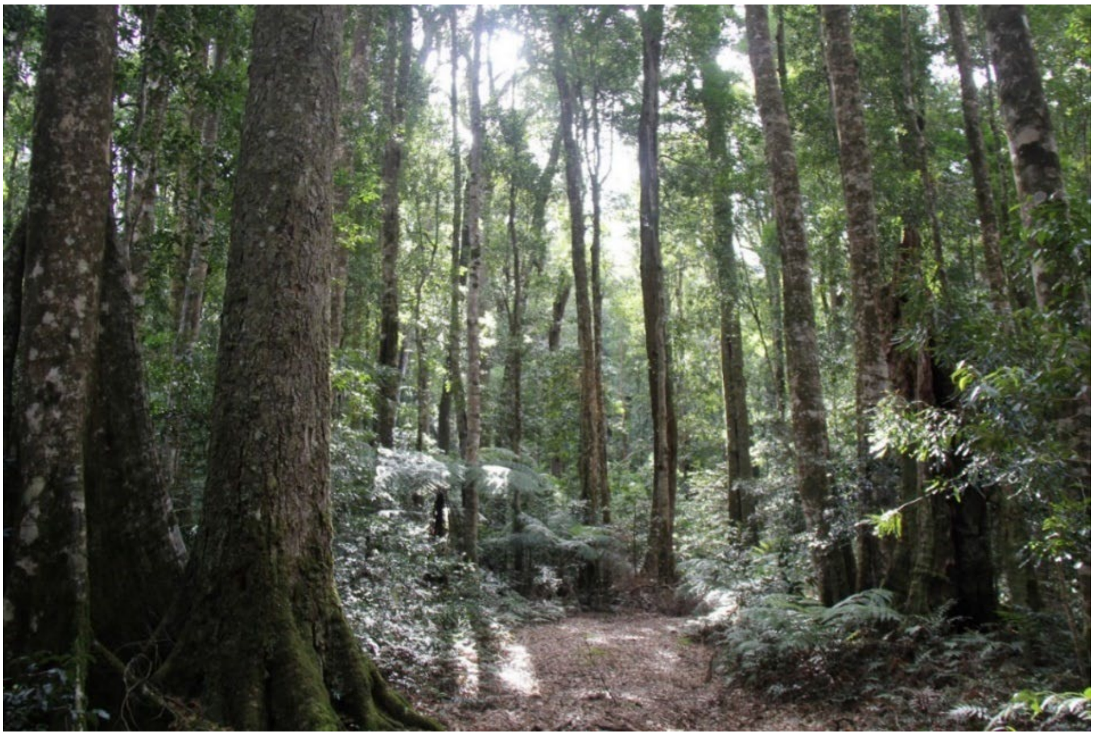

FIGURE 2: COOL TEMPERATE RAINFOREST MT BANDA BANDA WILLI WILLI NP. (IMAGE: ROSS PEACOCK).

*Nothofagus moorei* is a key canopy species of these forests, forming either the tallest canopy stratum or an emergent layer above the dense mixed species sub-canopy stratum. The finest examples of *Nothofagus moorei* - *Ceratopetalum apetalum* forests are considered to be those of Werrikimbe and Willi Willi National Parks. Here cool temperate rainforest occupies an altitudinal range of 900 – 1240 m with *N. moorei* forming an open canopy 25–40 m tall over a dense 15–25 m sub-canopy of *Ceratopetalum apetalum* and *Doryphora sassafras*. Approximately 15 additional sub-canopy rainforest tree species exhibiting strong relictual Gondwanan affinities occur in the rainforest community. There is a continuous understorey cover of ground fern species such as *Blechnum wattsii* and *Sticherus lobatus* and semi-woody vines such as *Ripogonum discolour*. The cool temperate rainforests of the Gondwana Rainforests are notable for their distinctive floristic assemblage and level of endemism (Bale et al. 1993), particularly of epiphytic and lithophytic lower plants (Franks et al. 2000, Downing et al. 2014).

The Antarctic Beech rainforests of Werrikimbe and Willi NP within the Hastings-Macleay Group of the Gondwana World Heritage property were subject to selective harvesting activity from the 1950s to early 1980s prior to their dedication as formal reserves. Timber harvesting focused on the recovery of high value rainforest timbers such as Sassafras (*Doryphora sassafras*), Prickly Ash (*Orites excelsus*), Coachwood (*Ceratopetalum apetalum*) and several other species. While *Nothofagus* was harvested, significant challenges from splitting and warping during processing and an unpredictable level of bole timber defect (7-30% of standing volume) led to its abandonment as preferred timber species. Trees were felled, and once the stems were identified as being defective, were left on the forest floor to eventually become substrates for epiphytic lower plants. The silvicultural systems in use at the time for temperate rainforest required a 50% canopy retention system, with the aim of optimising the retention of future growing stems and the maintenance of the rainforest canopy environment for sustaining post-logging regeneration. The canopy retention system also resulted in a significant proportion of post-harvesting canopy dieback (Baur 1987), leaving a legacy of rainforest stands in good to poor condition that were predicted to take a century to recover to their pre-harvest structure and composition (Horne and Gwalter 1987). The condition of these post-logging rainforest stands and their three-dimensional fuel and flammability characteristics increases the possibility of fire damage (Horne and Hickey 1991). Existing stand conditions may therefore be a key determinant of their vulnerability to the 2019/20 wildfire event.

## RAINFOREST STAND DYNAMICS

The growth and dynamic patterns of temperate rainforests in the study area are typical for un-even aged rainforest stands exhibiting episodic recruitment and irregular patterns of growth and mortality across species and time-frames.

FIGURE 3: STORM CANOPY DAMAGE TO TEMPERATE RAINFOREST IN WILLI WILLI NP FEBRUARY 2013. TREE FALLS AND CANOPY DAMAGE CREATES GAPS, WHICH RESULT IN THE RELEASE OF EXISTING SUPPRESSED SUB-CANOPY TREES (IMAGE: ROSS PEACOCK).

Tree mortality is a critical component of stand dynamics along with regeneration and growth. It is a normal process within forest stands and is generally assumed to be in balance with growth to sustain ecosystem processes. Tree mortality affects stand structure, community composition, and stand development processes, and has been recently hypothesised to be increasing globally due to a range of anthropogenic factors and drought (van Mantgem et al. 2009).

While tree growth is a variable and continuous process, mortality in rainforest trees can take many forms although it is usually size dependent and adopts annualised rates of 1-2% (Swaine et al. 1987). While tree growth is a variable and continuous process, mortality in rainforest trees tends to be episodic and is typically associated with periods of storm damage and low rainfall (Floyd 1989). Fifty-four percent of tree census periods ranging from 1959 to 2013 recorded no annual mortality of trees > 10 cm DBH. The mean annualized mortality rate was 0.75 % (95% CI 0.529-0.917, N=194). Tree mortality is generally higher in the slower growing sub-canopy species (Figure 5) than the canopy dominant species.

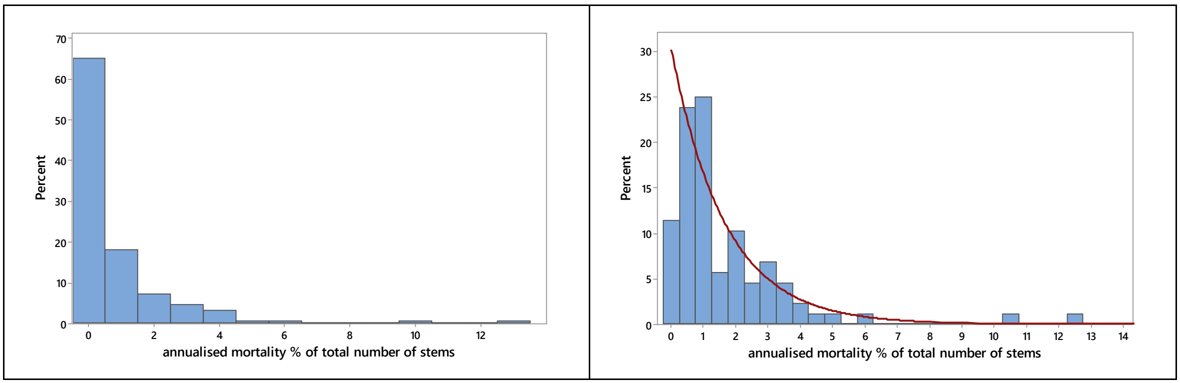

FIGURE 4: ANNUALISED TREE MORTALITY ACROSS 194 CENSUS PERIODS IN TEMPERATE RAINFOREST PERMANENT PLOTS WITHIN THE STUDY AREA. THE HISTOGRAM ON THE LEFT INCLUDES ALL DATA INCLUSIVE OF CENSUS PERIODS WITH NO MORTALITY, THE GRAPH ON THE RIGHT ONLY INCLUDES CENSUS PERIODS WITH MORTALITY.

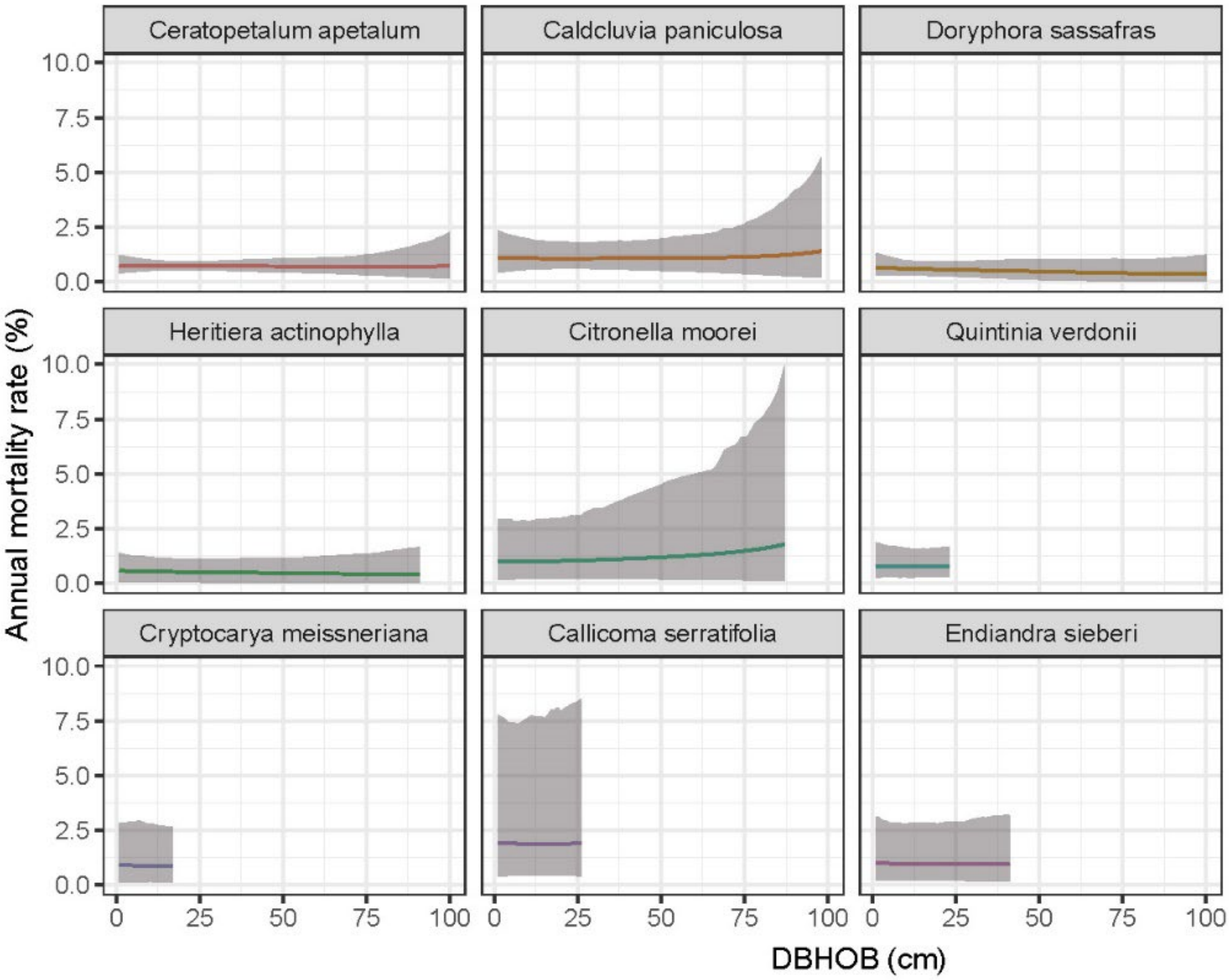

FIGURE 5: MODELLED RATES OF TREE SPECIES MORTALITY (AND 95% CI IN GREY) IN COOL TEMPERATE RAINFOREST, EASTERN DORRIGO NORTHERN NSW, 1944-2011. ANALYSIS BY RAPHAEL TROUVE, THE UNIVERSITY OF MELBOURNE

Stand structures are un-even aged or multi-aged, typical of the structures observed in the *Nothofagus cunninghamii* forests of northwestern Tasmania (Hickey and Felton 1987) and the Central Highlands of Victoria (Simkin and Baker 2008).

The stand basal areas (70–130 $m^2/ha^{-1}$, mean 83 $m^2/ha^{-1}$ Table 1, Figure 6) are some of the highest recorded in any NSW forest type and are substantially higher than those found in other rainforest types (Baur 1989). More than half of the stand basal area is made up of *Nothofagus* trees, although they represent only 17% of the total number of stems (Table 1). A large proportion of tree stems that are suppressed have originated as coppice shoots from the base of the tree or surficial roots. This results in individual trees with multiple stems of different ages.

Larger diameter canopy trees are primarily *Nothofagus moorei*. This is interpreted both in terms of their canopy dominant height, crown width and longevity, and the proportional reduction in large diameter *Ceratopetalum* trees which were selectively removed for the peeler sawmill at Yarras from the 1960s. Large diameter *Ceratopetalum* trees are more commonly encountered in unlogged stands (e.g. Fenwicks Scrub, Werrikimbe NP) or in inaccessible very steep streamside habitats. Mean stem diameter of *Ceratopetalum* in unlogged stands was 47.8 cm (95% CI 43.99-61.26, N=125). In contrast in logged rainforest, mean stem diameter was 25.1 cm (95% CI 12.8-32.5, N=630).

TABLE 1: CHARACTERISTIC STAND STRUCTURE AND TREE GROWTH RATES IN MATURE TEMPERATE RAINFOREST, WERRIKIMBE NP.

| Tree species | Basal Area ($m^2/ha^{-1}$) | Stem Density trees/$ha^{-1}$ | Mean Stem Diameter (cm) | Mean Tree Ht (m) | Mean Annual Increment ($mm/yr^{-1}$) |
|---|---|---|---|---|---|
| *Nothofagus moorei* | 40.7 | 160 | 47.0 | 18.1 | 4.3 |
| *Ceratopetalum apetalum* | 29.2 | 531 | 23.0 | 23.1 | 2.8 |
| *Doryphora sassafras* | 1.7 | 92 | 14.6 | 8.5 | 1.6 |
| *Tristaniopsis collina* | 1.6 | 6 | 57.4 | 24.6 | 1.8 |
| *Persoonia media* | 1.3 | 98 | 12.7 | 8.7 | 1.6 |
| *Orites excelsa* | 0.4 | 24 | 14.2 | 5.2 | 2.3 |
| *Schizomeria ovata* | 0.3 | 12 | 16.0 | 10.2 | 2.1 |
| *Cryptocarya meisneriana* | 0.1 | 12 | 11.4 | 4.3 | 1.7 |
| *Cryptocarya nova-anglica* | 0.1 | 6 | 11.9 | 9.0 | 1.5 |
| Total | 75.5 | 945 | 24.7 | | |

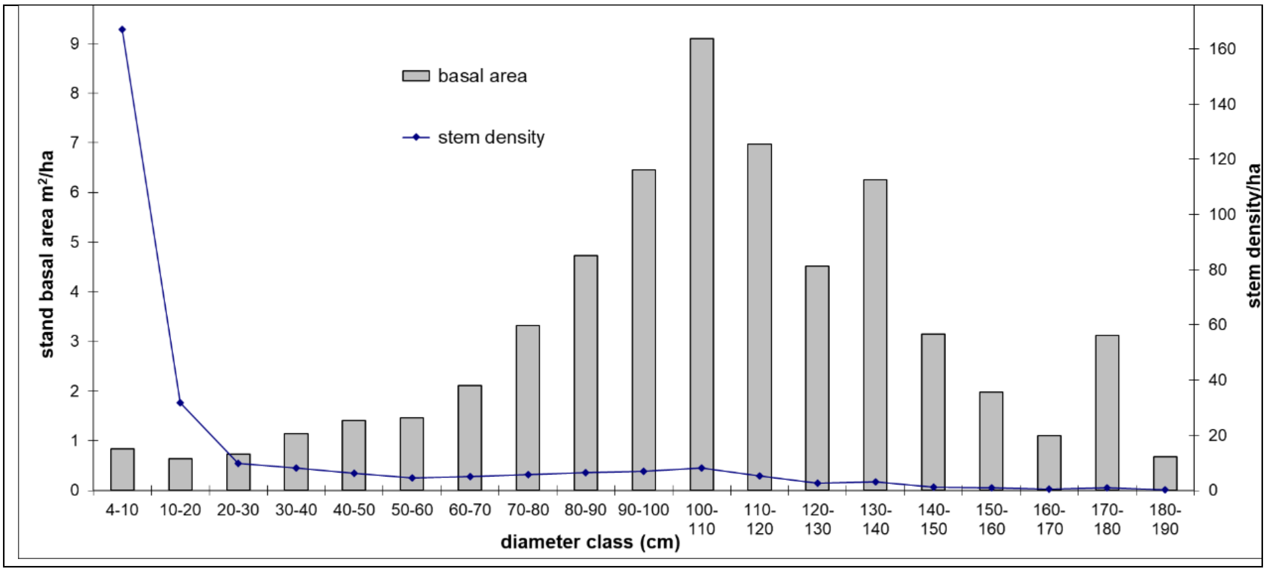

FIGURE 6: STAND STRUCTURE OF A SINGLE 3.8 HA INVENTORY PLOT, WERRIKIMBE NP. RECRUITMENT IS CONTINUOUS, WITH A WIDE VARIETY OF SIZE CLASSES PRESENT REFLECTING BOTH GROWTH SUPPRESSION, GROWTH RELEASE IN LIGHT GAPS AND MULTI-COHORT STEMS ON A SINGLE TREE. REGENERATION OF *NOTHOFAGUS MOOREI* IS PRIMARILY VIA BASAL STEM COPPICE, SUPPLEMENTED BY SEEDLING RECRUITMENT IN MAST YEARS. *CERATOPETALUM APETALUM* HOWEVER RELIES PRIMARILY ON ANNUAL SEEDLING RECRUITMENT. TREE GROWTH IS SLOW, WITH MANY TREES EXHIBITING ANNUAL DIAMETER GROWTH OF ONLY 1-2 MM PER YEAR.

Seedling recruitment patterns across the rainforest canopy tree species varies from species with strong masting characteristics to those with largely annual seed production. *Nothofagus moorei* is a masting species, typically exhibiting synchronous masting across northern NSW approximately three times per decade. Masting events were most recently recorded in January 2020, 2018, 2014 and 2011.

Masting results in an abundance of seed output in *Nothofagus moorei*. In January 2018 at Willi NP mean seed output of two and three-winged seeds measured in a series of seed traps was 7838 seeds/m2 (95% CI 4370-9009, N=12). Mean germination was 11.48% resulting in a mean of 908 seedlings per m2 at the dicotyledon and two-leaf pair stage one-two months later. Less than 1% of these seedlings persist to the three-leaf pair stage.

Stand growth rates (Figure 7) vary depending on species, size classes and canopy class with many trees having suppressed crowns of poor form due to competition and shading. Periods of negative stand growth increment are common (Figure 7). Tree growth is comparatively slow, with many trees exhibiting annual diameter growth of only 1-2 mm per year (Table 1). This is broadly similar to growth rates reported for *Nothofagus* rainforests in Tasmania (3 mm per year in Hickey and Felton 1987). Higher growth rates occur on trees with healthy crowns and access to canopy gaps. Growth release of suppressed stems occurs following disturbances such as storms creating canopy gaps. Prior to the dedication of the reserve network, suppressed stems were released from overstorey competition following selective harvesting.

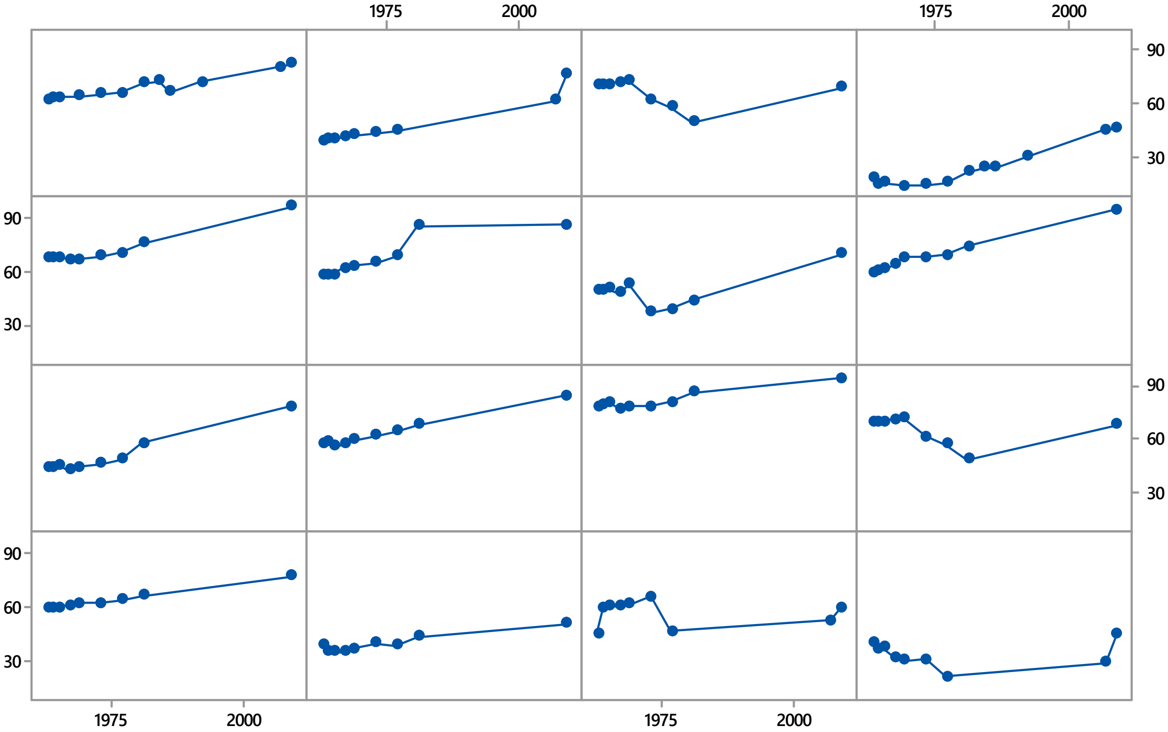

FIGURE 7: TIME SERIES OF STAND BASAL AREA $m^2\ ha^{-1}$ FOR SIXTEEN GROWTH PLOTS WITHIN TEMPERATE RAINFOREST AT WILLI WILLI AND WERRIKIMBE NP'S 1962-2011. MEAN ANNUAL BASAL AREA INCREMENT IS 0.47 $m^2\ ha^{-1}\ yr^{-1}$.

FIGURE 8: CROWN DIEBACK OF NOTHOFAGUS MOOREI WITH REGENERATING COHORT BENEATH, WERRIKIMBE NP 2014 (IMAGE: ROSS PEACOCK).

Ongoing crown dieback and mortality of canopy trees are most evident in stands with a history of wildfire and selective harvesting since the 1960s and 1970s (Figure 8). Preliminary data suggests dieback following wildfire damage is widespread across tree species and size classes (Figure 9, 10). The extent, mechanisms, and persistence of dieback characteristics in northern NSW temperate rainforests are largely unreported except for a single study near Dorrigo (Horne and Mackowsky 1987). Data from unpublished experiments established in the 1960s and 1970s examining the relationship between dieback and silvicultural prescriptions suggest that annual mortality rates of 0.75% (95% CI 0.52:0.91) are common and dieback can occur independently of tree diameter size classes (Figure 9-10) although there is a weak trend of an increasing incidence of dieback in larger diameter trees. Annual mortality rates for *Nothofagus* in Tasmania have been measured at 0.9%-1.6% for undisturbed sites, increasing to 3.1% for selectively logged sites (Elliot et al 1987, Packham 1991) Consequently the interaction of the 2019/20 wildfire season and existing canopy tree dieback patterns is unknown. Further analyses will be required to describe patterns of dieback in relation to tree size, species, canopy dominance, and past incidence of wildfire and selective harvesting.

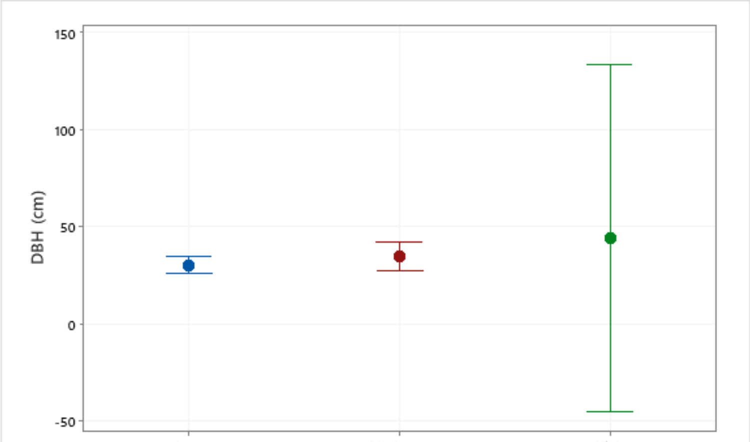

FIGURE 9: RELATIONSHIP BETWEEN RAINFOREST TREE DIEBACK AT WILLI WILLI NP FOLLOWING WILDFIRE DAMAGE IN 1956 (MEASURED IN 1962) AND TREE DIAMETER. DIEBACK WAS NOT RELATED TO TREE DIAMETER (ONE-WAY ANOVA [$F_{(1,108)}$ = 1.09, P=0.342]

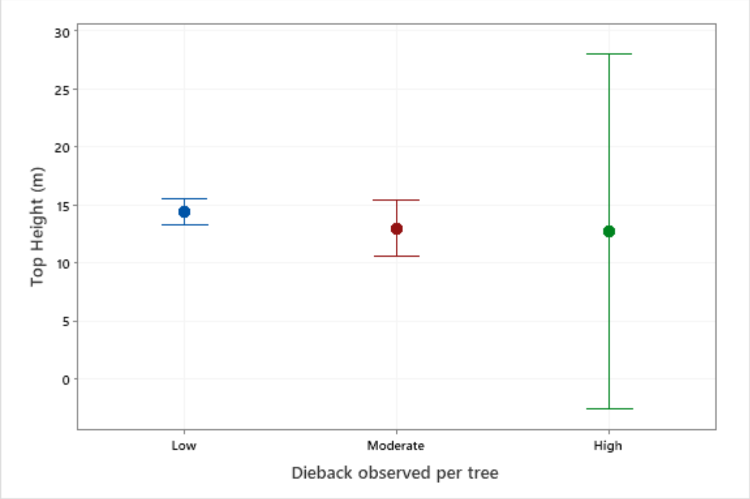

FIGURE 10: RELATIONSHIP BETWEEN RAINFOREST TREE DIEBACK AT WILLI WILLI NP FOLLOWING WILDFIRE DAMAGE IN 1956 (MEASURED IN 1962) AND TREE TOP HEIGHT. DIEBACK WAS NOT RELATED TO TREE TOP HEIGHT (ONE-WAY ANOVA [$F_{(1,78)}$ = 0.83, P=0.438]

## THE RAINFOREST CLIMATE

The climate of the study area is cool temperate, with a mean annual rainfall of 1920 mm and mean annual temperature of 14.6°C from 1959 to present. Relative humidity usually exceeds 90%. Fog and mist deposition is common all year and can contribute up to 30-40% of additional moisture input from canopy moisture stripping compared to orographic precipitation (Hutley et al 1997, Narsey et al 2020). Rainfall peaks in the summer months (Figure 13) with a mean of 197 rain days per year. Since 1960 mean annual temperature has increased by 1.5°C, a rate of increase at the high end of the scenarios outlined for projected global warming. Mean annual rainfall for the 1960-2019 period has decreased from a long-term average of 1920 mm to 1620 mm (Figure 11). 2019 was the driest year (881 mm) since local records began in Werrikimbe NP in 1959.

The understorey environment is typically low in photosynthetically active radiation (PAR 400-700 nm), with an average of only 11% of radiation at the canopy surface reaching the groundstorey and fuel layers (Figure 12). These very low light levels have implications both for profile fuel drying and the recruitment and growth of rainforest tree seedlings post-fire.

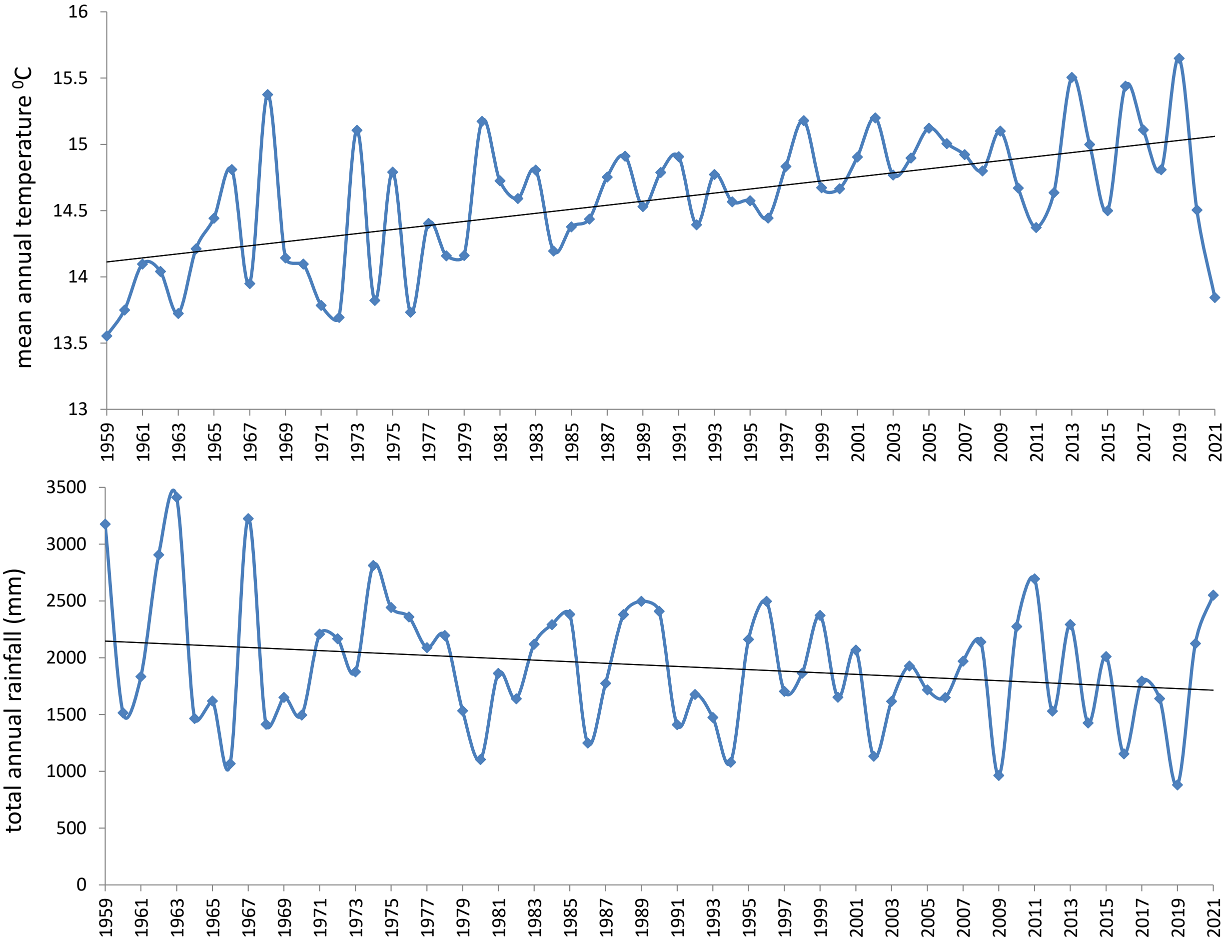

FIGURE 11: LONG-TERM CLIMATE RECORD WERRIMIMBE NP NORTHERN NSW 1959-2021 BASED ON LOCAL OBSERVATIONS FROM 2009 AND HISTORICAL DATA FROM BOM STATION 060068 FROM 1959. THE CLIMATE OF THE RAINFOREST STANDS IS CHANGING – MEAN ANNUAL TEMPERATURE IS INCREASING AND MEAN ANNUAL RAINFALL IS DECREASING.

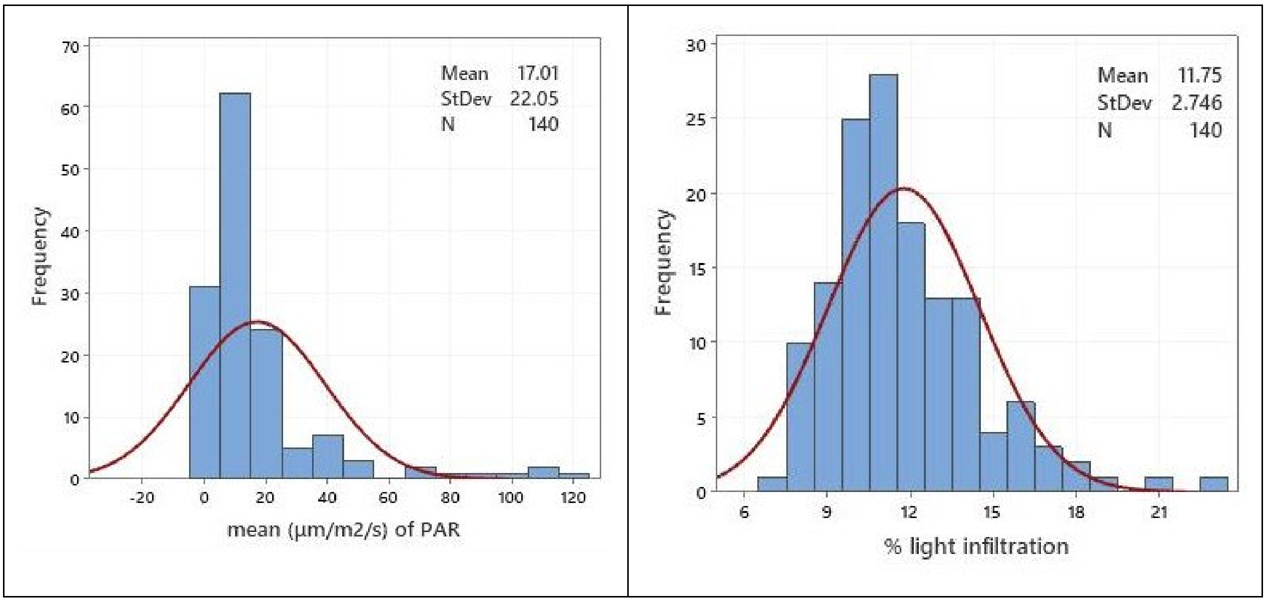

FIGURE 12: UNDERSTOREY LIGHT ENVIRONMENTS IN RAINFOREST ARE TYPICALLY LOW IN PHOTOSYNTHETICALLY ACTIVE RADIATION (PAR, 400 TO 700 NM) AND THE PERCENTAGE OF LIGHT INFILTRATING THROUGH THE DENSE MULTI-STRATA CANOPY AND SUB-CANOPY. DATA BASED ON 140 MEASUREMENTS IN WERRIKIMBE AND WILLI WILLI NATIONAL PARKS IN RAINFOREST USING A LICOR LI 250A LIGHT METER AND LI 190R QUANTUM SENSOR. LIGHT INFILTRATION REPRESENTS THE INSTANTANEOUS PERCENTAGE DIFFERENCE BETWEEN THE UNDERSTOREY LIGHT MEASUREMENT AND CORRESPONDING MEASUREMENT MADE IN A NEARBY OPEN AREA.

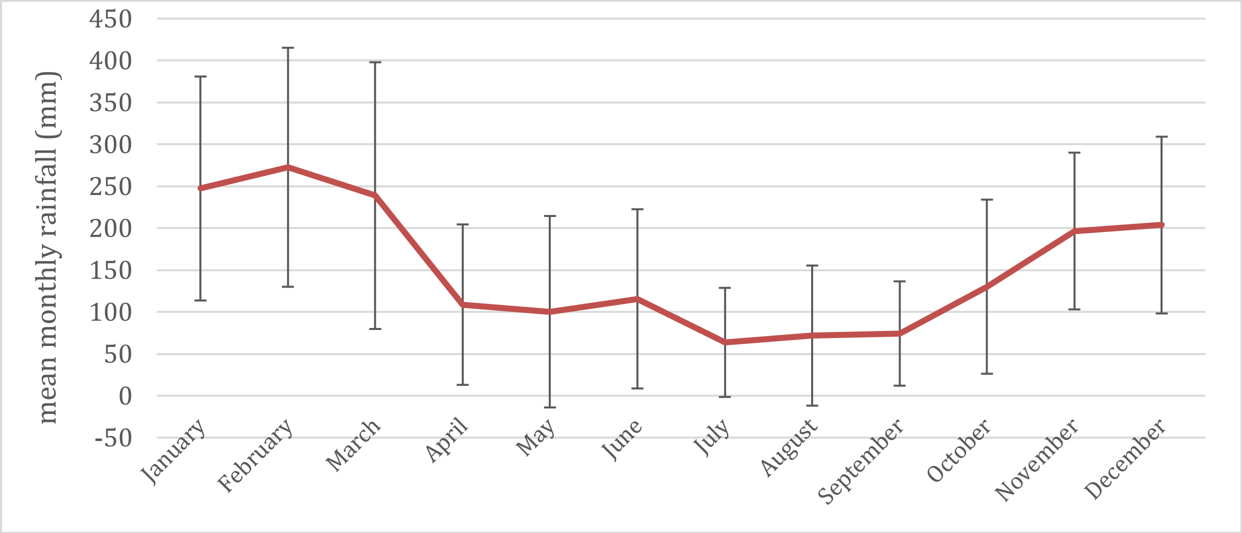

FIGURE 13: RAINFALL SEASONALITY WERRIMIMBE NP NORTHERN NSW 1990-2021 BASED ON LOCAL OBSERVATIONS FROM 2009-2021 AND HISTORICAL DATA FROM BOM STATION 060068 FROM 1959.

Rainfall peaks in the summer months with minima in July-August (Figure 13). As temperatures rise in spring, rainfall increases. Where a spring drought occurs with the decoupling of rising temperatures and soil moisture, the spring growth flush of new apical shoots exhibits critical low turgor pressure, and drought damage may occur. Drought damage at Werrikimbe NP has been observed with as much as 30% of the new season's growth in *Nothofagus moorei* being lost (Figure 14). Severe drought can lead to heightened tree mortality in *Nothofagus* (Howard 1973), particularly individuals with more variable or slower growth rates (Suarez 2004).

FIGURE 14: *NOTHOFAGUS MOOREI* SEASONAL SPRING GROWTH FLUSH UNDER NORMAL CONDITIONS (LEFT) AND SEVERE WATER STRESS (RIGHT) IN NOVEMBER 2012. (IMAGE: ROSS PEACOCK).

## PREVIOUS WILDFIRE SEASONS

The observations of fire-fighters responding to wildfires across the Gondwana Rainforests during the 2019/20 season are consistent with early reports from the 1950s at Mt Boss describing rainforests in the study area as '*green scrub areas inflammable under extreme conditions*'. Similarly, early reports of wildfires failing to penetrate warm temperate rainforests in Victoria were attributed to high canopy foliage density of the rainforest dominant *Acmena smithii* (Ashton 1970). The weather conditions experienced in northern NSW in mid-November 2019 (i.e., extended spring drought, high temperatures, low humidity, low soil moisture, and anomalous north and westerly winds) were almost identical to those experienced in mid-November 2018 in the Mackay Highlands of Queensland that led to rainforest, including cloud rainforests in the Eungella-Crediton region, igniting (Hines et al. 2020).

The challenges faced by fire-fighting authorities and land managers in the Gondwana Rainforests during the 2019/20 wildfire season in NSW were perhaps not as unprecedented as the contemporary accounts suggested. Multiple areas of the Gondwana rainforest in the northern rivers area of NSW have burnt since 1915 (Table 1) during conditions analogous to 2019/20 where the fire season is preceded by extended spring drought. The spring drought conditions of 1968 led to severe drought stress and rainforest canopy leaf fall and following ignition, all rainforest in Limpinwood Nature Reserve burnt. The wildfires at Conglomerate and surrounding State Forests west of Coffs Harbour in 1968 were so extreme that a NSW Forestry Commission fire report noted that '*even the rainforests were burning*'. Baur (1989) describes the extreme conditions under which rainforests ignite and support a running and that these fires are largely confined to surface litter. Notably, historical and contemporary accounts all refer to these fires occurring in late spring.

Similar conditions were experienced associated with positive anomalies of the Southern Annular Mode leading to warmer and drier conditions and widespread fires in Gondwana rainforest throughout Patagonia in 2011 and 2015, and in Gondwana rainforest in southwestern and north-western Tasmania in 2015 and 2019.

TABLE 1: NOTABLE FIRE SEASONS IN NORTHERN NSW WHERE RAINFORESTS WERE RECORDED AS BURNT.

| Year | Location details and date | Source |
|---|---|---|
| 1915 | Mt Pikapene State Forest August 1915<br>Nimbin, Tabulum, Tenterfield | Baur 1989<br>'*Widespread fires on north coast*'. 4 11 1915,<br>'*country from Wauchope to Kempsey is more or less burnt out*' Sydney Morning Herald 15/11/1915<br>Widespread fires around Nimbin and northern tablelands (Northern Star (Lismore) 30 Oct 1915) |
| 1918-1919 | North coast NSW | Trove reports |
| 1926 | North coast NSW<br>15-16/10/1926<br>19/12/1926 | Luke 1970<br>Widespread fires on north coast. 15 10 1926 fires raging in Hastings district. *All mountains between Wauchope and northern tablelands ablaze*. Sydney Morning Herald 16/10/1926<br>Sydney Morning Herald 11/11/1926 *Bushfires ranging every part of Hastings shire*<br>Sydney Morning Herald 19 12 1926 *fires uncontrolled for at least a month between Armidale and Kempsey* |
| 1951 | Mt Boss SF 18th October 1951 | Widespread fires on NSW north coast. 18th October 1951 4046 ha of state forest burnt at Mt Boss |
| 1956/57 | Mt Boss SF compartment 77, now Willi Willi and Werrikimbe NP burns (230 ha) November 1956 | most of Mt Boss compartment 77 burnt by wildfire, including rainforest (Forestry Commission of NSW (1957) Fire Plan for Bellangry Sub-district (Wauchope District) 1957/1958 season dated 5th April 1957 and Baur 1989) |
| 1968 | Conglomerate and surrounding States Forests west of Coffs Harbour ignited in November 1968<br>Toonunbar NP, Mt Nothofagus, the Nightcap Range, and the Border Trail | Extreme wildfire conditions experienced with temperatures exceeding 45$^0$C. 'Even the rainforests were burning' Luke 1970<br>Matthew Wiseman, NSW NPWS |
| 1993/1994 | Werrikimbe NP, Little Bull Creek, Threadneedle Creek, Clonmel complex 29th December 1993 to 6-8th January 1994. Fire complex burnt 23,900 ha. Crown fires, spotting distances of up to 3 km, | 'although rainforest was critical to the containment of fires, there has been severe damage (crown scorch) on rainforest margins near Crown Lookout Road (now Werrikimbe NP), likely to result in effective retreat of that type' (NPWS/SFNSW debrief report 7th March 1994) |
| 2002 | Moppy Creek Barrington Tops NP 09/11/2002 | Fire spots into rainforest on Barrington Tops Forest Road and progresses slowly as a litter fire. |
| 2012 | Macleay River wildfire 02/11/2012 to 17/11/2012 | 59898 ha burnt<br>SITREP of 22/10/12 stated part of the control strategy for Cochrane Division was 'significant areas of rainforest may hold fire before falling back to roads and trails' |
| 2013 | Werrikimbe NP Brushy Mountain Complex fire 2-11th November 2013 | 13503 ha burnt. Wildfire burnt numerous rainforest patches and margins in Racecourse – Spokes section. 'Fire continues to burn in and around rainforest west of Banda Banda Trail' IAP 05/11/13. |
| 2014 | Yarrowitch Junction wildfire Oxley Wild Rivers NP 26/10/2014 to 21/11/2014 | 5334 ha burnt. Lightning ignition. Significant impacts on dry rainforest. |
| 2017 | Youdales Hut sector Oxley Wild Rivers NP 28/9/2017<br>Skink Trail November-01 December 2017 | Fires cross creek containment lines<br>Fire burns downslope through brushbox rainforest profile fuels |
| 2018 | Double Head Trail 5 November 2018 | Dry rainforest impacted |
| 2019 | Bees Nest Mt Hyland NR October 2019<br>Gilmores Gully Kempsey 16/08/2019<br>Morora Creek East Dorrigo 06/09/2019<br>Stockyard East fire 25/10/2019 to 27/12/2019 | Sub tropical rainforest and wet sclerophyll impacted. Aerial ignition used as part of containment strategy. Fire extends across 100,000 ha<br>From November to December 2019 multiple fires across northern NSW impact on rainforest. |

## THE 2019/20 WILDFIRE SEASON IN NSW

The 2019/20 wildfire season in NSW extended from 19th July 2019 to 2nd March 2020 (Figure 15) and saw biodiversity impacts on a scale, duration and intensity not seen perhaps since 1915 or 1968. The wildfires were unusually large and intense and led to significant damage to forest structures, biodiversity, built assets, as well as loss of human lives. The 2019/20 wildfire season has been described as unprecedented (Collins et al 2021) or the most extreme event, for at least the preceding 20 years, based on a global analysis of the proportion of the temperate and broadleaf mixed forest biome burnt (Boer et al 2020, Wheeling 2020). It was characterized by record-breaking temperatures, an extended spring drought, low fuel and soil moistures, high winds and repeated periods of severe fire weather in southeastern Australia (Deb et al. 2020, Filkov *et al*. 2020, Nolan *et al*. 2020, Boer *et al*. 2020). For the 2019/20 season more than half of the July–December drought was driven by record excursions of the Indian Ocean dipole and Southern Annular Mode (van Oldenborgh et al. 2020). The impact of extended periods of low rainfall over the late winter to spring period was exacerbated by periods of record high temperatures, higher rates of evaporation, and very low soil moisture across large areas of Australia during 2019. Many forests exhibited symptoms of drought stress and increased canopy leaf fall during a period of significant increases in the Forest Fire Danger Index. The resultant increase in available fuel saw 5.5M ha of forest burn in NSW, and the emergence of several megafire complexes that severely stressed the capacity of fire-fighting authorities to respond in a conventional manner.

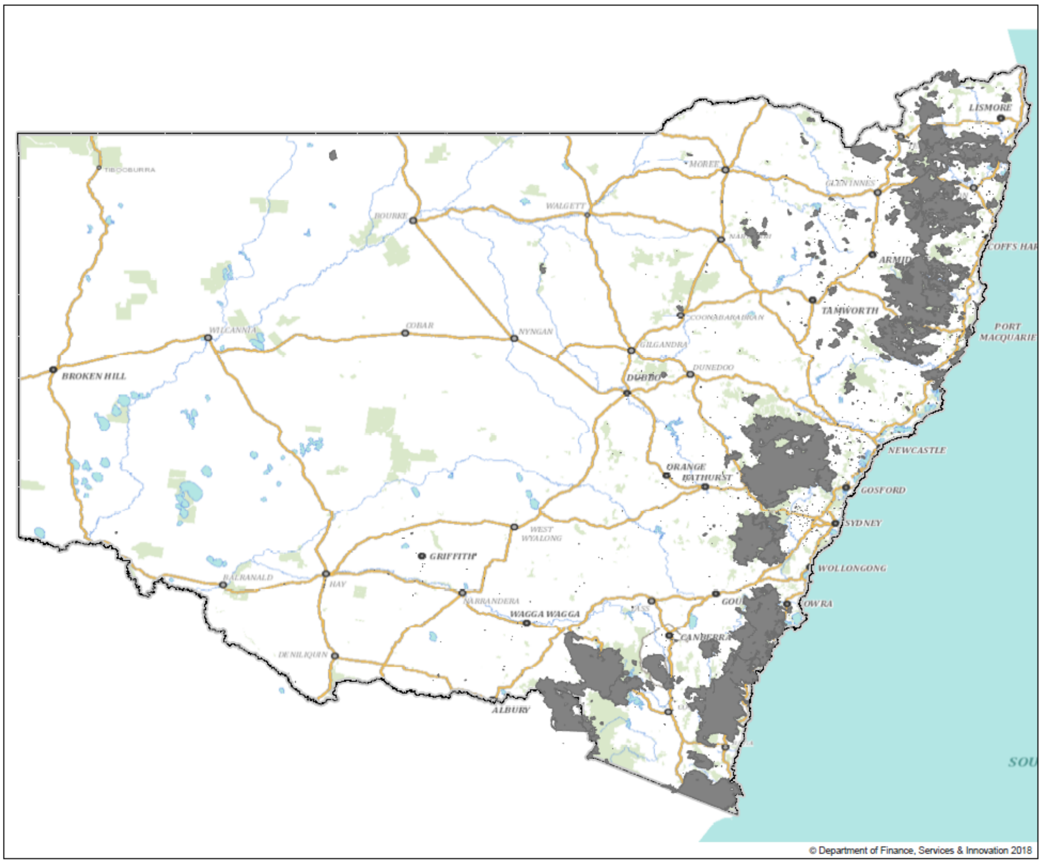

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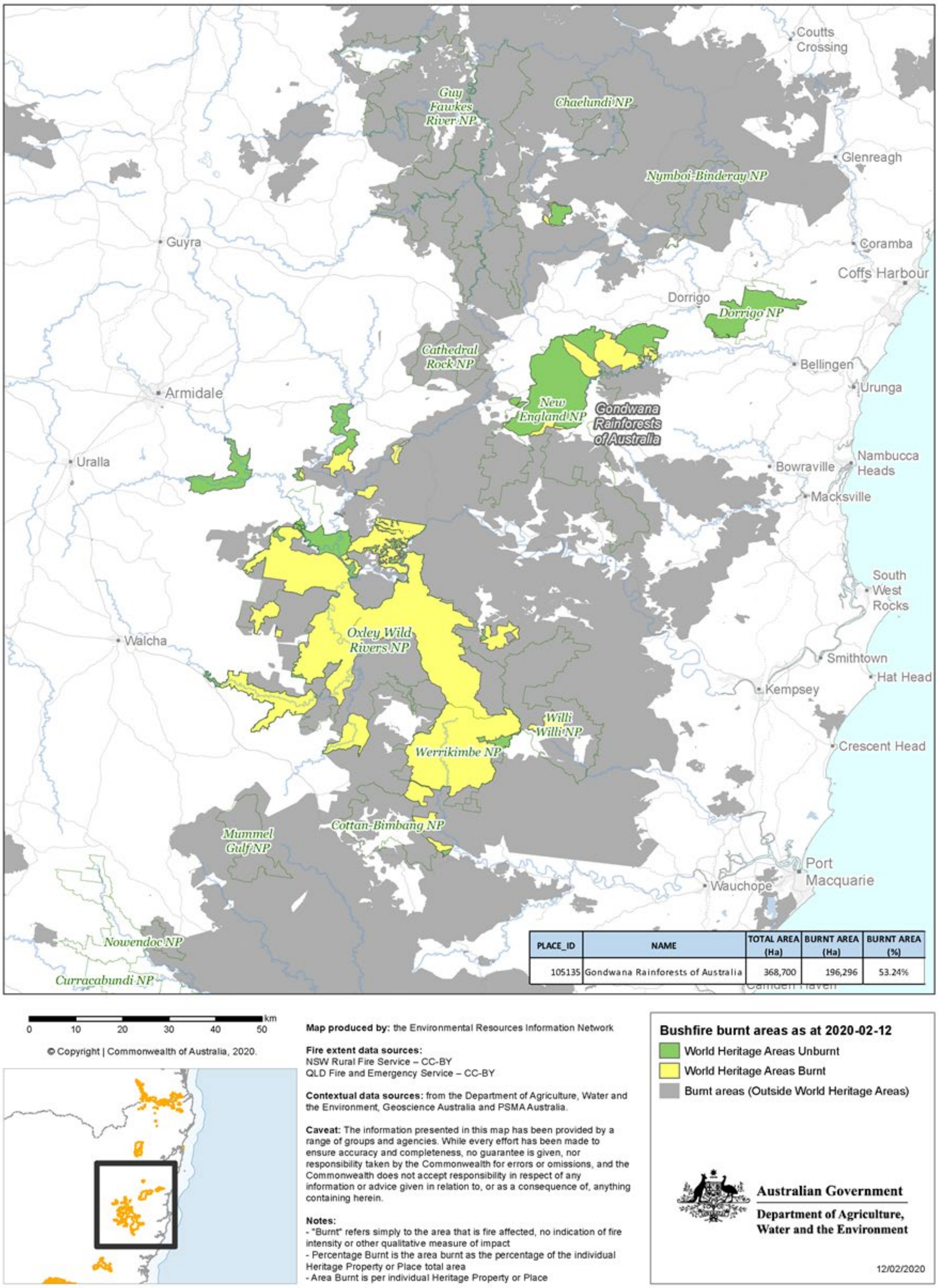
FIGURE 15: THE EXTENT OF THE 2019/20 WILDFIRE SEASON IN NSW - 19TH JULY 2019 TO 2ND MARCH 2020. 5.5 MILLION HECTARES BURNT SOURCE: NSW RURAL FIRE SERVICE

Multiple remote area fires, including those in the Gondwana Rainforests (Figure 16) burnt where fire-fighting authorities had limited options for direct attack and containment except for the use of aviation resources and hard containment along fire trails.



| PLACE_ID | NAME | TOTAL AREA (Ha) | BURNT AREA (Ha) | BURNT AREA (%) |
|---|---|---|---|---|
| 105135 | Gondwana Rainforests of Australia | 368,700 | 196,296 | 53.24% |

**Map produced by:** the Environmental Resources Information Network

**Fire extent data sources:**
NSW Rural Fire Service – CC-BY
QLD Fire and Emergency Service – CC-BY

**Contextual data sources:** from the Department of Agriculture, Water and the Environment, Geoscience Australia and PSMA Australia.

**Caveat:** The information presented in this map has been provided by a range of groups and agencies. While every effort has been made to ensure accuracy and completeness, no guarantee is given, nor responsibility taken by the Commonwealth for errors or omissions, and the Commonwealth does not accept responsibility in respect of any information or advice given in relation to, or as a consequence of, anything containing herein.

**Notes:**
- "Burnt" refers simply to the area that is fire affected, no indication of fire intensity or other qualitative measure of impact
- Percentage Burnt is the area burnt as the percentage of the individual Heritage Property or Place total area
- Area Burnt is per individual Heritage Property or Place

**Bushfire burnt areas as at 2020-02-12**

| | |
|---|---|
| 🟩 | World Heritage Areas Unburnt |
| 🟨 | World Heritage Areas Burnt |
| ▨ | Burnt areas (Outside World Heritage Areas) |

Australian Government
Department of Agriculture, Water and the Environment

12/02/2020

FIGURE 16: EXTENT OF WILDFIRE IMPACTS TO CENTRAL SECTION OF GONDWANA RAINFORESTS OF AUSTRALIA WORLD HERITAGE PROPERTY. (https://www.environment.gov.au/heritage/publications/gondwana-rainforests-state-conservation-update-april-2020)

The wildfires were a complex extreme event that had multiple contributing factors occurring across a range of spatial and temporal scales (Deb et al. 2020). Fire risk was elevated, leading to increased fire intensity on several key days, with synoptic conditions that resulted in low humidity and anomalous westerly winds leading to the prediction of extreme and catastrophic conditions.

The general pattern of landscape fire behaviour observed by the fire-fighting authorities adjacent to Gondwana rainforests in November 2019 was as follows. Wildfires, igniting following lightning activity in dry forest communities (Figure 17), are driven by strong north-westerly winds and low relative humidity's to spread rapidly along north and west-facing slopes. Strong winds combined with very strong convective activity were presumed to be present, based on observed downwind spotting from ridge top to ridge top. This mechanism allows the fire to be spread from ridge top to ridge top across areas of less flammable vegetation. The progression of fires on protected leeward eastern slopes is slow under backing fire conditions, and where fires approach wet sclerophyll and other sclerophyll communities with a rainforest understorey the rate of spread slows further until the rainforest communities are encountered.

FIGURE 17: BEES NEST SECTOR FIRE IN GUY FAWKES RIVER NATIONAL PARK SEPTEMBER 2019. TYPICAL FIRE BEHAVIOUR IN EUCALYPTUS FOREST COMMUNITIES. IMAGE: NSW NPWS.

Under conditions of changing fuel characteristics, fire spread into the rainforest stands is generally limited to 30m from the ecotone (Matthew Wiseman, NSW NPWS pers. comm.), or up to 100 m on upward slopes. Fire spread was generally contained by rainforest stands, although exceptions did occur, for example, Mt Nothofagus (Matthew Wiseman, NSW NPWS pers. comm.) and Cathedral Rock National Park (Colin Bale pers. comm.).

## THE STOCKYARD EAST WILDFIRE

The Stockyard East fire (NSW RFS Incident No. 19102552802, Figure 18, 19) started on 25/10/2019 and was declared out on 27/12/2019 after burning 86,934 ha across private land, State Forest and National Park. The suspected ignition source was lightning. Where it burnt across areas impacted by the 2013 and 2015 wildfires it was observed to be much more severe than either of those fires. Where it burnt into rainforest it was burning across stands not known to have seen wildfire impacts since 1956. Elsewhere the fire re-burnt the margins of rainforest stands that had been burnt in the Brushy Mountain Complex wildfire of 2013. Evidence of heavy ember attack (ember density was predicted to be 6/m$^2$) was widespread across rainforest stands, often leading to localized ignition events within the rainforest and short fire runs burning small areas typically <100 $m^2$.

The Stockyard East fire was a complex of several fires that merged over a two-month period and were eventually managed as a single incident. The fire had multiple fronts and flanks, continuous spotting behaviour (estimated up to 2.3-3.6 km), and sectors which at times were considered contained and later, following changes in weather and fuel conditions, determined to be active. Much of the fire complex burnt in remote and inaccessible forested terrain with few options for direct attack except from the air. On 07 11 2019 an incident weather forecast for this fire predicted a maximum temperature of 36° C at 1500 hours, a dew point of -2° C, RH of 9%, wind from the WNW gusting to 40 km/hr, and an FFDI of 62. Localized weather recording closer to the fire indicated a temperature of 29° C and RH of 17% in rainforest at 1330 hours. Volumetric soil moisture at 1330 hours, recorded every 30 minutes, was 10.3%. Fire intensity in the *Eucalyptus* forest surrounding the rainforest was predicted to be 7000-8000 kW/$m^2$ (high to very high), and a flank rate of spread approximately 700 m/hr.

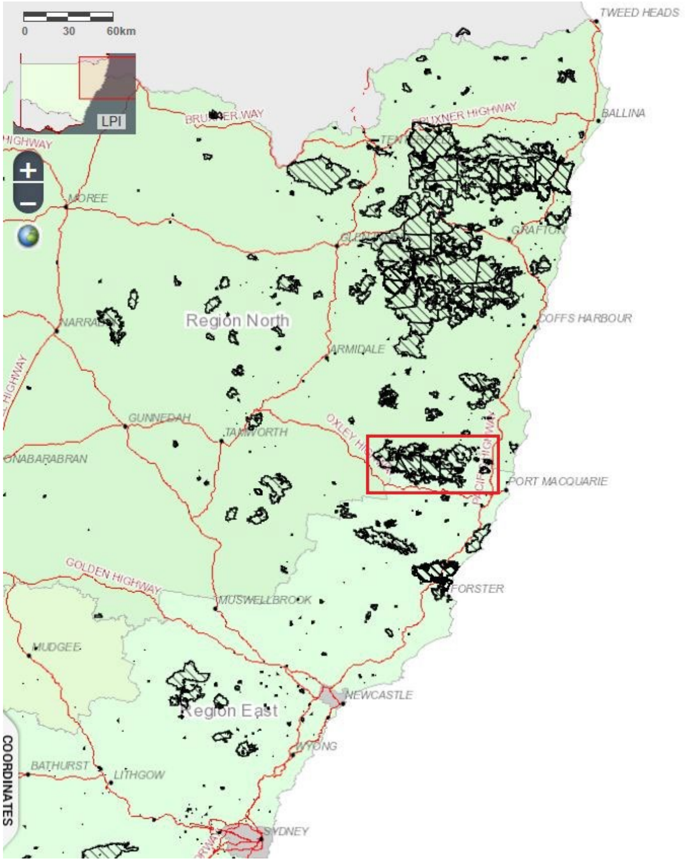


FIGURE 18: THE STOCKYARD EAST FIRE EXTENT DATED 12/01/2020. THE STOCKYARD EAST WILDFIRE AND THE CONTIGUOUS MINES ROAD BRIL AND DINGO CREEK WILDFIRES ARE IN THE INSERT BOX.

Most of the areas sampled in this study were burnt by the Stockyard East fire on 7-9th November 2019 based on line-scan mapping of active fire edges. The exception was Plot 1 sampled at Mt Banda Banda Willi Willi NP; it was considered to have been burnt closer to 7th December 2019 (Figure 20).

FIGURE 19: THE STOCKYARD EAST FIRE BURNT AND SCORCHED THE PERIMETER OF RAINFOREST NEAR SPOKES MOUNTAIN, WERRIKIMBE NP AND SPREAD UNDERNEATH THE CANOPY BURNING GROUND FUELS AND UNDERSTOREY VEGETATION. IMAGE: NSW NPWS.

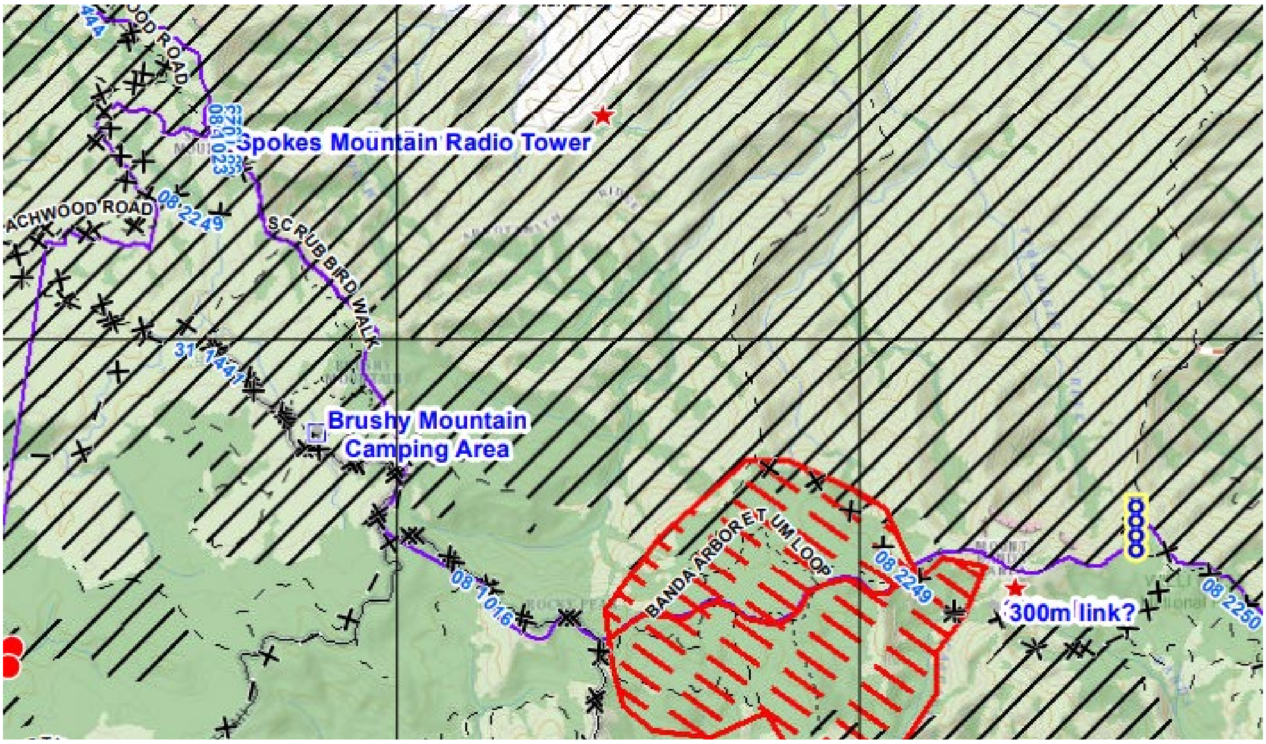


FIGURE 20: THE STOCKYARD EAST INCIDENT BASED ON NSW RFS MAPPING DATED 28/11/2019. THE SHADED AREA IS BURNT, THE MAIN ASSETS REQUIRING PROTECTION INCLUDE THE SPOKES MOUNTAIN GOVERNMENT RADIO TOWER AND THE MT BANDA BANDA RAINFOREST STAND (MAPPED AS A RED EXCLUSION AREA). FIRE EDGE DATES BASED ON LINE SCANS ARE GIVEN AS '08 2249' INDICATING THE ACTIVE FIRE OCCURRED ON 08 11 2019 AT 2249 HOURS.

## HOW MUCH RAINFOREST BURNT IN THE 2019/20 WILDFIRE SEASON IN NSW

Obtaining an accurate assessment of the extent of the rainforest that burnt in NSW in the 2019/20 fire season is a key requirement for informing recovery planning. Several different approaches exist, but they vary depending on how the extent of the fire ground is mapped and which rainforest typology and spatial extent data are utilised. Initial estimates suggested 37% of NSW's rainforest formations had been affected and 54% of the NSW sections of the Gondwana Rainforests burnt (NSW Department of Planning, Industry and Environment 2020a). This latter figure received widespread international attention although the majority of the vegetation burnt in the Gondwana Rainforests was Wet Sclerophyll Forest (Grassy), not rainforest.

Across NSW, 18.1% of the total area of rainforest vegetation classes experienced either moderate, high or extreme severity wildfire (Table 2). The proportion of each class varied, the greatest impacts being experienced in Dry Rainforest and Northern Warm Temperate Rainforest. In the Gondwana Rainforests 8.6% of the 112,145 ha of rainforest burnt to some measurable degree (Table 3). These wildfires affected 17 of the 28 reserves in the NSW section of the Gondwana Rainforests (NSW Department of Planning, Industry and Environment 2020). Across both NSW and the Gondwana Rainforests, the greatest impacts of fire in rainforests were in the Dry Rainforest and Northern Warm Temperate Rainforest types.

The extent of the fire impacts were greatest in the Hastings-Macleay, New England and Washpool-Gibraltar Range sections of the Gondwana Rainforests(Table 4). In these sections, Dry Rainforest, Northern Warm Temperate Rainforest and Subtropical Rainforest were subject to the greatest proportional extent of fire. Within the Hastings-Macleay section, the focus of this study, the highest severity impacts were detected remotely in Subtropical Rainforest (Table 5).

TABLE 2: THE NSW EXTENT OF FIRE EFFECTED RAINFOREST FROM THE 2019/20 WILDIFE SEASON. THE SUMMARY IS BASED ON THE INTERSECTION OF THE NSW RAINFOREST VEGETATION CLASSES WITH BOTH THE NSW RFS FIRE EXTENT POLYGON AND FESMv2 SENTINEL PRODUCT.

| NSW Vegetation Class | Total NSW area (ha) | Unburnt area (ha) | Unburnt and within ICON fire extent area (ha) | Low severity FESM area (ha) | Moderate severity FESM area (ha) | High severity FESM area (ha) | Extreme severity FESM area (ha) | Total burnt (FESM) area (ha) | Proportion burnt (FESM) |
|---|---|---|---|---|---|---|---|---|---|
| Cool Temperate Rainforests | 20,978 | 17,679 | 946 | 433 | 729 | 566 | 626 | 2,354 | 11.2% |
| Dry Rainforests | 214,938 | 113,346 | 41,955 | 20,463 | 15,640 | 19,142 | 4,391 | 59,637 | 27.7% |
| Littoral Rainforests | 7,151 | 6,391 | 172 | 162 | 164 | 169 | 93 | 760 | 9.6% |
| Northern Warm Temperate Rainforests | 239,811 | 136,433 | 61,152 | 15,957 | 14,644 | 9,462 | 2,163 | 42,226 | 17.6% |
| Subtropical Rainforests | 275,321 | 203,870 | 33,061 | 12,056 | 14,355 | 10,636 | 1,343 | 38,390 | 13.9% |
| Western Vine Thickets | 29,819 | 29,455 | 144 | 11 | 104 | 97 | 7 | 219 | 0.7% |
| **total** | **788,999** | | | | | | | **143,587** | **18.1%** |

TABLE 3: THE GONDWANA RAINFORESTS OF AUSTRALIA (NSW PORTION) EXTENT OF FIRE EFFECTED RAINFOREST FROM THE 2019/20 WILDIFE SEASON. THE SUMMARY IS BASED ON THE INTERSECTION OF THE NSW RAINFOREST VEGETATION CLASSES WITH BOTH THE NSW RFS FIRE EXTENT POLYGON AND FESMv2 SENTINEL PRODUCT.

| NSW Vegetation Class | Gondwana area | Unburnt area (ha) | Unburnt and within ICON fire extent area (ha) | Low severity FESM area (ha) | Moderate severity FESM area (ha) | High severity FESM area (ha) | Extreme severity FESM area (ha) | Total burnt (FESM) area (ha) | Proportion burnt (FESM) |
|---|---|---|---|---|---|---|---|---|---|
| Cool Temperate Rainforests | 10,170 | 10,070 | 304 | 67 | 30 | 3 | 0 | 101 | 0.09% |
| Dry Rainforests | 19,311 | 15,430 | 8,335 | 1,199 | 1,814 | 789 | 78 | 3,881 | 20% |
| Littoral Rainforests | 116 | 113 | 2 | 3 | 0 | 0 | 0 | 3 | 2.3% |
| Northern Warm Temperate Rainforests | 42,727 | 38,175 | 12,645 | 1,582 | 2,063 | 811 | 96 | 4,553 | 10.6% |
| Subtropical Rainforests | 39,820 | 38,703 | 1,886 | 440 | 503 | 157 | 17 | 1,117 | 2.8% |
| Western Vine Thickets | - | - | - | - | - | - | - | - | |
| **total** | **112,145** | | | | | | | **9,654** | **8.6%** |

TABLE 4: PROPORTION OF NSW VEGETATION CLASSES WITHIN THE MAPPED FIRE GROUND (AS A % OF CLASS AREA WITHIN EACH GONDWANA SERIAL PROPERTY SECTION)

| | Proportion within fire ground (% of NSW Vegetation Class area in Gondwana Serial Property section) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **NSW Vegetation Class** | **Barrington Tops Area** | **Coastal Forests** | **Focal Peak** | **Hastings - Macleay** | **Main Range** | **New England** | **Tweed Caldera** | **Washpool - Gibraltar Range** |
| Cool Temperate Rainforests | 3% | 0% | 0% | 28% | 0% | 5% | 0% | 0% |
| Dry Rainforests | 0% | 0% | 5% | 85% | 0% | 30% | 0% | 63% |
| Littoral Rainforests | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| Northern Warm Temperate Rainforests | 2% | 0% | 5% | 88% | 0% | 9% | 9% | 63% |
| Subtropical Rainforests | 8% | 0% | 3% | 91% | 0% | 24% | 0% | 80% |
| Western Vine Thickets | | | | | | | | |

TABLE 5: PROPORTION OF NSW VEGETATION CLASSES WITHIN FESMV2 FIRE SEVERITY CLASSES (AS A % OF CLASS AREA WITHIN THE HASTINGS MACLEAY GONDWANA SERIAL PROPERTY SECTION)

| | Proportion within fire severity (FESM) class (% of NSW Vegetation Class area in Gondwana Serial Property section) | | | | | |
|---|---|---|---|---|---|---|
| **NSW Vegetation Class** | **Unburnt** | **Non-FESM burnt area** | **Low severity** | **Moderate severity** | **High severity** | **Extreme severity** |
| Cool Temperate Rainforests | 72% | 26% | 0% | 2% | 0% | 0% |
| Dry Rainforests | 14% | 59% | 8% | 12% | 6% | 1% |
| Littoral Rainforests | 0% | 0% | 0% | 0% | 0% | 0% |
| Northern Warm Temperate Rainforests | 12% | 65% | 7% | 11% | 5% | 0% |
| Subtropical Rainforests | 7% | 28% | 16% | 26% | 21% | 1% |
| Western Vine Thickets | | | | | | |

# OBJECTIVES

## TEMPERATE RAINFOREST FIRE BEHAVIOUR IN NORTHERN NSW

Fire behaviour is typically characterised within vegetation communities using parameters including weather and, fuel hazard, mass, and moisture content. Predicting fire behaviour for a running fire then incorporates antecedent conditions using a drought factor to predict and model ignition, rate and direction of spread, flame length, spotting distance and density, fire intensity and type. Fire behaviour analysts use this information to develop fire behaviour predictions, devise containment strategies, estimate mop-up difficulties, issue alerts and warnings and estimate risk to assets. Fire behaviour predictions are typically viewed spatially through time-stamped raster based tools when integrated with predicted weather, atmospheric stability predictions, landscape features, fuel continuity and more. Despite there being a range of fire behaviour models in Australia for non-rainforest types (Cruz et al. 2015), no generalised fire behaviour model currently exists for rainforests. There has been an implicit assumption that a fire behaviour model for rainforests is not required because they are unlikely to ignite and support a running fire. The New Zealand Fire Behavior Prediction System (Pearce et al 2012) includes a fire spread model modified for podocarp forest, which has the potential to be adapted to cool temperate rainforest communities in Tasmania (Figure 21, Love et al. 2019).

FIGURE 21: THE GELL RIVER FIRE WESTERN TASMANIA JANUARY 2019. FIRE SPREAD FOLLOWS FUEL AND VEGETATION BOUNDARIES. (IMAGE ALEX MURPHY, NSW RFS)

Early ecological studies highlighted the sensitivity of Australian rainforests to fire (Francis 1951, Webb 1968) and its role in determining patterns of rainforest landscape distribution in the absence of abrupt changes in factors such as soil nutrients. While this theory was corroborated in many subsequent studies of rainforest boundary dynamics across eastern Australia, the occurrence and impacts of wildfires within rainforest stands were rarely examined beyond the issue of the dynamics of vegetation boundaries adjacent to more flammable vegetation communities (Figure 21). Consequently, the prevailing paradigm of the sensitivity of Australian rainforests to fire persisted (e.g., Howard 1981), despite numerous but perhaps less well documented counter-examples of rainforest resilience (e.g., Ridley and Gardner 1961, Chesterfield et al. 1991, Baker et al. 2012) and regeneration (Tolsma et al. 2019) post-fire. The persistence and resilience of rainforests to fire has been reported from subtropical rainforests in Queensland (Hegarty 2020), and from cool temperate rainforests in Victoria and Tasmania (Gilbert 1959, Howard 1969, Baker et al. 2012, Tolsma et al. 2019) and warm temperate rainforests in Victoria (McMahon 1987, 1992). A peculiar phenomenon referred to as surface or litter fires has been described where low intensity fires burn through low biomass fuels and few changes in the structure of composition of the closed rainforest canopy occurs (McMahon 1987, 1992). Examples of fires have been described from East Gippsland (Victoria) in 1983 and at the Moppy Creek fire at Barrington Tops in 1968 (Floyd 1990) and November 2002 (RFS ICON) when a wildfire traversed underneath a *Nothofagus moorei* rainforest stand to continue burning surrounding Eucalyptus forest. On the margins of these same stands, crown fires will damage the rainforest canopy trees (Figure 21).

In Tasmanian mixed forests, Gilbert (1959) argued that fire *per se* was not antagonistic to rainforest persistence, it is the fire-free period following fire that determines regeneration success or failure. The same concept was developed further in Victoria as the tolerable fire interval (Cheal 2010) and in NSW using fire interval guidelines based on plant functional types (Bradstock and Kenny 2003). Cheal described a minimum tolerable fire interval for both low severity patchy and high severity fires of 80 years in cool temperate rainforest. Such stands were considered flammable in only rare conditions such as following the extended droughts that preceded the 1983 and 2009 fire seasons. Catastrophic wildfires are rare in these environments, in Victoria occurring at intervals of 100-500 years (Peel 1999) Using this scheme, rainforests were expected to take many decades to recover from fire, and few (if any) species were considered adapted to regenerate post-fire, and most are damaged by fire.

*Nothofagus moorei* has been assessed as a vulnerable species in the global Red List assessment (Baldwin et al. 2018). This was primarily due to the impacts of wildfire, global warming and habitat loss from historic clearing. The Baldwin assessment did, however, note that fires do not penetrate far into rainforest and that the species can regenerate and persist post-fire, albeit with some loss of genetic diversity.

Assessing the impacts of the 2019/20 fire season on the extent of NSW's rainforests is dependent on the rainforest type, its condition pre-fire, the length of time since the last fire, its landscape context, the severity of the localised impacts, the dryness thresholds that occurred on the fire ground, and the post-fire climatic conditions. Each is relevant to recovery planning, and several projects are currently underway (NSW Department of Planning, Industry and Environment 2020c, Eco Logical Australia 2020) to provide an explicit risk framework for addressing these issues as part of recovery planning prioritisation process.

FIGURE 21: WILDFIRE DAMAGE TO RAINFOREST MARGINS, WERRI-KIMBE NATIONAL PARK. THE ADVANCING EDGE OF *CERATO-PETALUM* AND *CALLICOMA* IS LARGELY FIRE-KILLED AND CROWN SCORCH AND PARTIAL CONSUMPTION HAS OCCURRED TO *NOTHOFAGUS* TREES FORMING THE EMERGENT STRATUM. WEST-FACING STANDS ARE BEING SUBJECT TO REPEATED FIRE IMPACTS WHERE THEY COINCIDE WITH TRADITIONAL FIRE PATHS. (IMAGE: ROSS PEACOCK)

## Research questions

This study plans to focus on the following research questions, each of which will assist with informing priorities for post-fire recovery actions:

> How much rainforest burnt in the Gondwana Rainforests in 2019/20 and did the impacts vary across rainforest types?
>
> Is there evidence for changing patterns of landscape wildfire activity in north-eastern NSW?
>
> What are the characteristics of the wildfires that burnt into rainforest?
>
> Can an understanding of rainforest fuel biomass, moisture content, and dynamics improve our understanding of fire behaviour in these ecosystems?
>
> Can a remotely measured fire severity metric assist with understanding the outcomes of wildfires for rainforest canopy condition?
>
> Does post-fire tree regeneration vary amongst rainforest tree species
>
> How do rainforest tree species ignite and is mortality related to tree size

# METHODS

The Hastings-Macleay section of the Gondwana Rainforests was selected for this study because it has an extensive range of pre-fire permanent plot measurements to provide a baseline for post-fire analysis. In addition, it has detailed long-term climate, fuel accumulation, wildfire and management records. High-resolution, post-fire imagery was available to validate the survey stratification design and the first author had 15 years of direct local research experience in the region and had been deployed as a fire-fighter to wildfire incidents as part of a fire-fighting authority.

## SURVEY DESIGN

The objective of the survey was to estimate structural and functional responses of rainforest stands to varying severities of wildfire impacts. Stratification was employed to reduce the variance in the sample and improve the power to detect change. The forest stands were stratified by vegetation type (temperate rainforest and non-rainforest) and a classification of fire severity (Table 6, Gibson et al. 2020). Ancillary information employed in the stratification process included digital aerial photography, remote sensing and local knowledge of the behaviour of the Stockyard East wildfire incident.

The fire impacts in rainforests were characterized using permanent plots. Plots were selected if field verification confirmed they met the sample stratification criteria of being within mapped temperate rainforest and the targeted fire severity class. They also needed to represent a homogeneous stand of forest where evidence of confounding disturbances was absent. Unburnt sites were selected using the same criteria, although for cost-effectiveness the approach utilized existing long-term plot data in the same study region. Locations that met the design criteria but failed field verification checks were excluded and additional sites were identified. A stratified random approach to selecting the sampling locations could not be employed due to the logistical constraints of working in remote reserves and because of the known limitations of the fire severity model in accurately classifying land with dense tree canopies and low severity understorey fires. A *post hoc* stratification approach to addressing the classification error in the severity classes was assessed but considered impractical to implement.

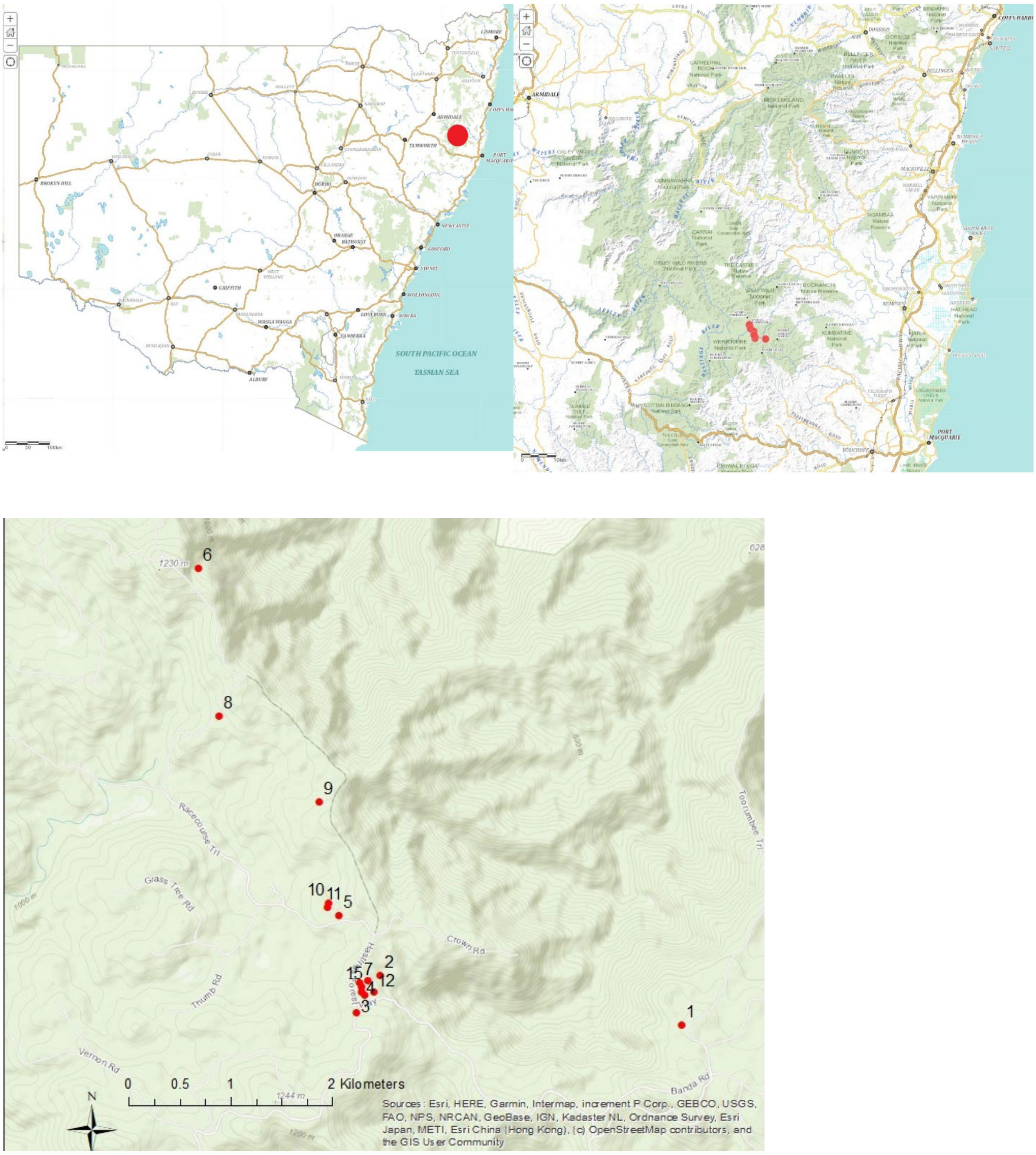
Fire severity was the primary stratification variable because it is a standardised metric associated with the loss of biomass caused by fire. The NSW statewide severity map (FESM, Gibson et al. 2020) has standardized classes to allow comparison of different fire severities across the landscape. The FESM severity classes are described in Table 6.

TABLE 6: NSW STATEWIDE FIRE SEVERITY CLASSIFICATION (GIBSON et al. 2020)

| Fire severity (FESM) classes | Definition | % foliage fire affected |
|---|---|---|
| Extreme Severity | Full canopy consumption | >50% canopy biomass consumed, |
| High Severity | Complete canopy scorch, partial canopy consumption | >90 % canopy scorched, <50% canopy consumed |
| Moderate Severity | Partial canopy scorch | 20-90% canopy scorched |
| Low Severity | Burnt understory, unburnt canopy | > 10% burnt understorey, >90% green canopy |
| Unburnt | Unburnt areas within fire boundary. Canopy and understorey both unburnt. | 0% canopy and understorey burnt |

## FIELD MEASUREMENT

The study area is situated on the mid-north coast of NSW approximately 80km north-west of Port Macquarie (Figure 22). Eleven permanent plots were established in the Hastings-Macleay portion of the Gondwana Rainforests between June and November 2020, and a further four existing permanent plots within the study area that were originally established in 1962 and measured repeatedly were incorporated (Table 6). The 11 plots were burnt in the Stockyard East fire in November 2019. A reconnaissance was undertaken in December 2019 to assess the extent and severity of the fire damage and document initial patterns of tree damage. Permanent plots were established within the targeted fire severity class (Figure 23) once verification checks (e.g., Southwell 2020) to ensure that the mapped severity class matched the field class were completed.



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

FIGURE 22: LOCATION OF STUDY AREA AND POSITION IN NORTHERN NSW

The fire severity class for each plot was extracted from the FESMv3 fire severity spatial model using bilinear interpolation of the pixel values intersecting a 15m radius buffer around the plot coordinates. Using the fire severity spatial attribution to classify the plots, four were recorded in the unburnt class, four in the low severity class, six in the moderate, and one in high severity class (Table 7). No temperate rainforest locations were classified as belonging to the high to extreme fire severity classes using this averaging approach.

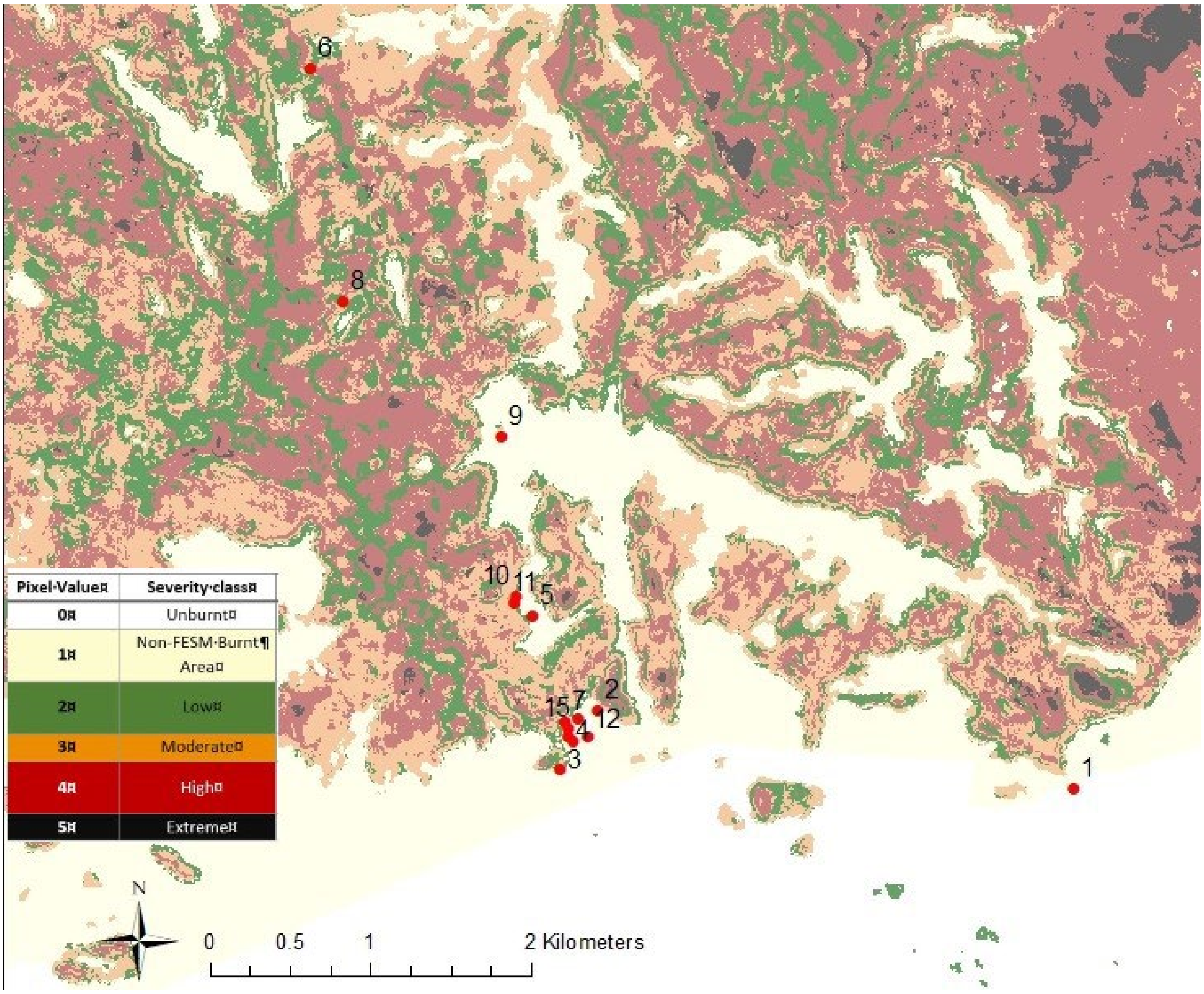


FIGURE 23: LOCATION OF SAMPLED PERMANENT PLOTS AND FIRE SEVERITY CLASSES.

TABLE 7: SAMPLING LOCATIONS, FIRE SEVERITY CLASSES AND STAND CHARACTERISTICS IN THE HASTINGS-MACLEAY SECTION OF THE GRA.

| No | plot_ID | Zone | Easting | Northing | Latitude | Longitude | Elevation (m) | plot size (ha) | Fire severity class (FESMv3 December 2020) | Basal Area $m^2/ha^{-1}$ | Number of stems/ha$^{-1}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Willi Willi NP Plot 1 | 56 J | 443084 | 6552648 | -31.15878 | 152.4028 | 1060 | 0.09 | Low | 91.4 | 43 |
| 2 | Werrikimbe NP plot 2 | 56 J | 440124 | 6553138 | -31.15420 | 152.3718 | 1099 | 0.09 | Low | 53.3 | 68 |
| 3 | Werrikimbe NP plot 3 | 56 J | 439911 | 6552765 | -31.15756 | 152.3695 | 1120 | 0.09 | Moderate | 80.3 | 114 |
| 4 | Werrikimbe NP plot 4 | 56 J | 439834 | 6552785 | -31.15566 | 152.3698 | 1117 | 0.09 | Moderate | 101.9 | 161 |
| 5 | Werrikimbe NP plot 5 | 56 J | 438155 | 6556799 | -31.14885 | 152.3676 | 1084 | 0.09 | Low | 95.1 | 104 |
| 6 | Werrikimbe NP plot 6 | 56 J | 438155 | 6556799 | -31.12096 | 152.3514 | 1240 | 0.09 | Low | 134.6 | 41 |
| 7 | Werrikimbe NP plot 7 | 56 J | 439820 | 6552875 | -31.15646 | 152.3686 | 1130 | 0.09 | Moderate | 69.1 | 143 |
| 8 | Werrikimbe NP plot 8 | 56 J | 438436 | 6555491 | -31.13278 | 152.3542 | 1086 | 0.09 | High | 114.9 | 68 |
| 9 | Werrikimbe NP plot 9 | 56 J | 439524 | 6554875 | -31.13881 | 152.3656 | 1100 | 0.09 | Moderate | 149.2 | 50 |
| 10 | Werrikimbe NP plot 10 | 56 J | 439618 | 6553832 | -31.14781 | 152.3665 | 1094 | 0.09 | Moderate | 115.9 | 51 |
| 11 | Werrikimbe NP plot 11 | 56 J | 439606 | 6553790 | -31.14819 | 152.3664 | 1092 | 0.09 | Moderate | 150.6 | 61 |
| 12 | Willi Willi NP D04201_A plot 12 | 56 J | 440062 | 6552961 | -31.15571 | 152.3711 | 1112 | 0.1619 | Unburnt | 80.8 | 153 |
| 13 | Willi Willi NP D04201_B plot 13 | 56 J | 439982 | 6552931 | -31.15597 | 152.3702 | 1120 | 0.1619 | Unburnt | 84.0 | 129 |
| 14 | Willi Willi NP D04201_C plot 14 | 56 J | 440008 | 6553073 | -31.15471 | 152.3705 | 1109 | 0.1619 | Unburnt | 55.0 | 197 |
| 15 | Willi Willi NP D04201_D plot 15 | 56 J | 439946 | 6553018 | -31.15519 | 152.3699 | 1119 | 0.1619 | Unburnt | 44.9 | 171 |

## TREE ATTRIBUTES

Each permanent plot consisted of a 0.09 or 0.1619 ha square or oblong plot marked with steel pegs on each corner and a painted reference peg at which GPS co-ordinates were recorded. Within each plot a range of tree-level attributes was recorded (Figure 24, Appendix 1), and each tree was marked with temporary paint when measured to avoid accidental re-measurement. Tree measurement protocols followed those used in permanent inventory plots established by the Forestry Corporation of NSW and its predecessors. The tree attributes have their origins in the northern NSW rainforest dynamic plot measurement program active from the 1930s to 1990s, permitting the incorporation of an extensive database of long-term measurements into the study. The range of attributes measured per tree encompassed species, tree form, dominance, existing damage, size, evidence of fire impacts, regeneration modes, and health (Appendix 1). Twenty-two species of tree were measured across 1554 individual trees (Table 8).

FIGURE 24: STANDARD INVENTORY PLOT MEASUREMENT PROTOCOLS WERE FOLLOWED PERMITTING THE INCORPORATION OF AN EXTENSIVE DATABASE OF LONG-TERM MEASUREMENTS INTO THE STUDY. TREES WERE MARKED WITH TEMPORARY PAINT TO AVOID ACCIDENTAL RE-MEASUREMENT. PLOTS ARE PERMANENTLY MARKED WITH STEEL PEGS TO FACILITATE FURTHER STUDY.

TABLE 8: TREE SPECIES RECORDED IN PLOTS, ORDERED BY FREQUENCY.

| Tree species | Count | Tree species | Count |
|---|---|---|---|
| *Ceratopetalum apetalum* | 630 | *Elaeocarpus reticulatus* | 6 |
| *Nothofagus moorei* | 517 | *Quintinia sieberi* | 6 |
| *Doryphora sassafras* | 123 | *Quintinia verdonii* | 5 |
| *Callicoma serratifolia* | 89 | *Acmena smithii* | 3 |
| *Orites excelsus* | 49 | *Tristaniopsis collina* | 3 |
| *Cryptocarya meissneriana* | 33 | *Acacia melanoxylon* | 2 |
| *Ackama paniculata* | 30 | *Acacia elata* | 2 |
| *Persoonia media* | 22 | *Schizomeria ovata* | 2 |
| *Eucalyptus obliqua* | 11 | *Sloanea woollsii* | 2 |
| *Eucalyptus andrewsii* | 9 | *Banksia integrifolia* | 1 |
| *Cryptocarya foveolata* | 8 | *Pittosporum undulatum* | 1 |
|  |  |  | 1554 |

# FINDINGS

## HISTORIC ANALYSIS OF SPATIAL PATTERNS OF LANDSCAPE SCALE WILDFIRES

In the study area, which is defined by the headwaters of the Forbes and Wilson Rivers, wildfires have been recorded in 1957 (Baur 1989) the 1960s, and every decade since (Figures 23-26). The traditional fire path consists of wildfires originating from dry lightning storms and accidental or arson ignitions in western sections of Werrikimbe NP and adjacent grazing properties. Historically, they have moved from the west to the east across the landscape (Figure 22). As the wildfires move east, the fire front gradually narrows and multiple fronts and flanks emerge due to landscape variation in fuels and topography. Typically, a second fire from the north will make a simultaneous run to the south to merge with the western fire to form a much larger fire complex with multiple fronts and flanks. The analysis of impacts of multiple fires in the study area over a period of 60 years suggests a re-occurring landscape pattern where the western edges of the larger rainforest stands are repeatedly subject to wildfires, and the smaller stands can be impacted on all edges (Figure 25). A sufficiently intense wildfire will burn mature cool temperate rainforest from a fire front or flank, however the field evidence suggests rainforests subject to ember attack did not sustain a fire beyond a short fire run. Evidence from repeated fires suggests the fire fronts are the problem, not the spotting fires.

## HISTORIC ANALYSIS OF FIRE SEASON ONSET AND LENGTH

Multiple reviews of global patterns of wildfire behaviour record an increase in the length of fire seasons as temperatures rise, lightning strikes increase and spring droughts lengthen and become more intense (Bradstock 2010, Collins et al. 2021, Jolly 2015). In almost all cases, these studies are not projecting an increase in the length of the fire season, rather they are projecting an increase in the length of season fire weather conditions. The two differ, one is constrained by the depth of fire records, one by meteorological metrics. Mapping of fires from satellite sources is frequently possible only from approximately 2000 making the detection of longer-term trends problematic. For this study, we combined data from operational fire mapping sources, and where these were not available, Forestry Commission of NSW District archival fire reports, to analyse changes in the annual portion of northern NSW burnt monthly since 1951. In the 1950s the peak fire month, measured as the month with the greatest area burnt per month as a proportion of the total annual area burnt, was November (Figure 31). In the 1960-70s the peak fire month was September; since 2000 the peak fire month has been October. Over the past 70 years the peak month of wildfire has advanced by several months and, consequently, now coincides with the driest months of the year.

The 2019/20 wildfire is the largest and most severe event recorded in the study area since forest and national park management records and mapping commenced in 1956. It is noteworthy that much of the eucalypt forests and woodlands providing the landscape matrix for temperate rainforest also burnt in 1994 and 2013 indicating that in 2019 fuel loads across the broader landscape were not necessarily high or at their equilibrium mass. This is consistent with broader landscape analyses suggesting fuel loads generally do not limit fire activity compared to the significance of ignition sources, fire weather and fuel moisture content.

This is a key consideration for any discussion of options for reconfigured fuel management objectives.

FIGURE 25: LARGE LANDSCAPE SCALE WILDFIRES DRIVEN BY NORTHERN AND WESTERLY WINDS ARE A SIGNIFICANT AND INCREASING THREAT TO RAINFOREST MARGINS. SPOKES SECTOR OF WERRIKIMBE NP FOLLOWING RACECOURSE TRAIL WILDFIRE IN 2013. THE UNBURNT VEGETATION IS TEMPERATE RAINFOREST. (IMAGE: NSW NPWS)

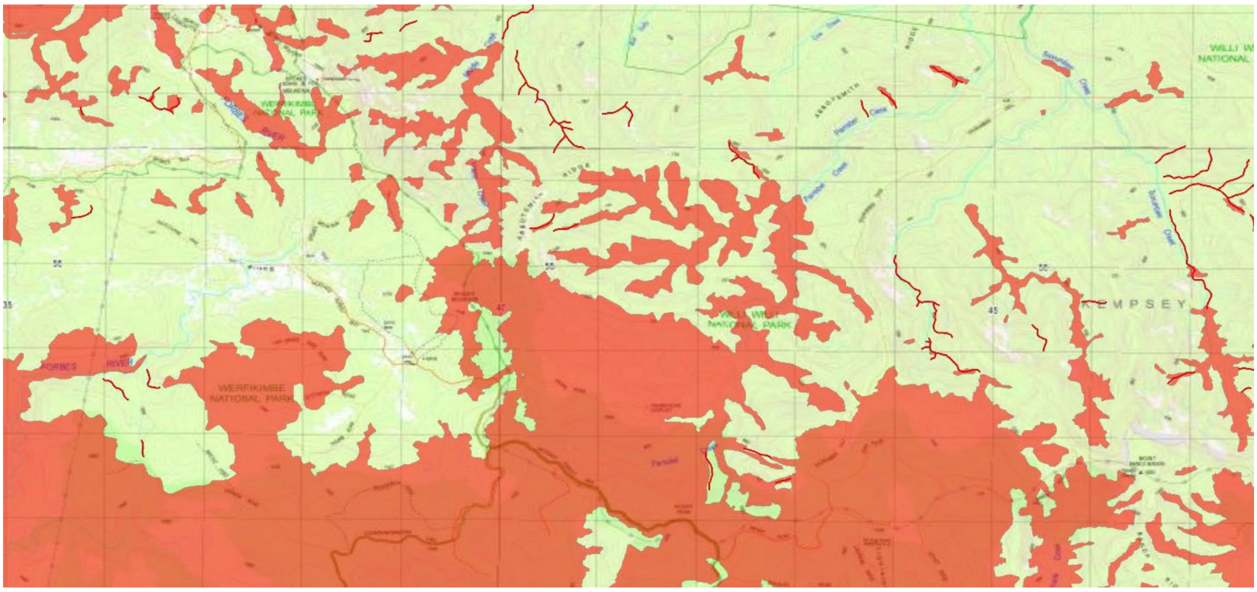


FIGURE 26: THE DISTRIBUTION OF RAINFOREST (SHADED RED) IN THE STUDY AREA. SOURCE: RAINFOREST MAPPING FOR NE NSW. VIS ID 3887 WWW.SEED.NSW.GOV.AU

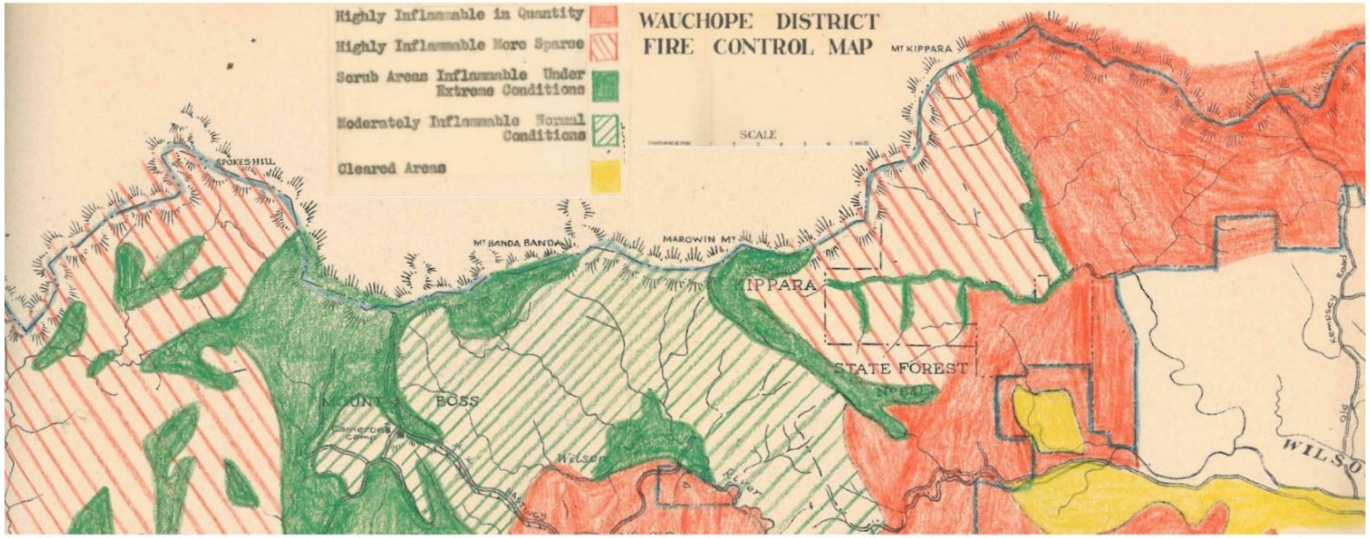
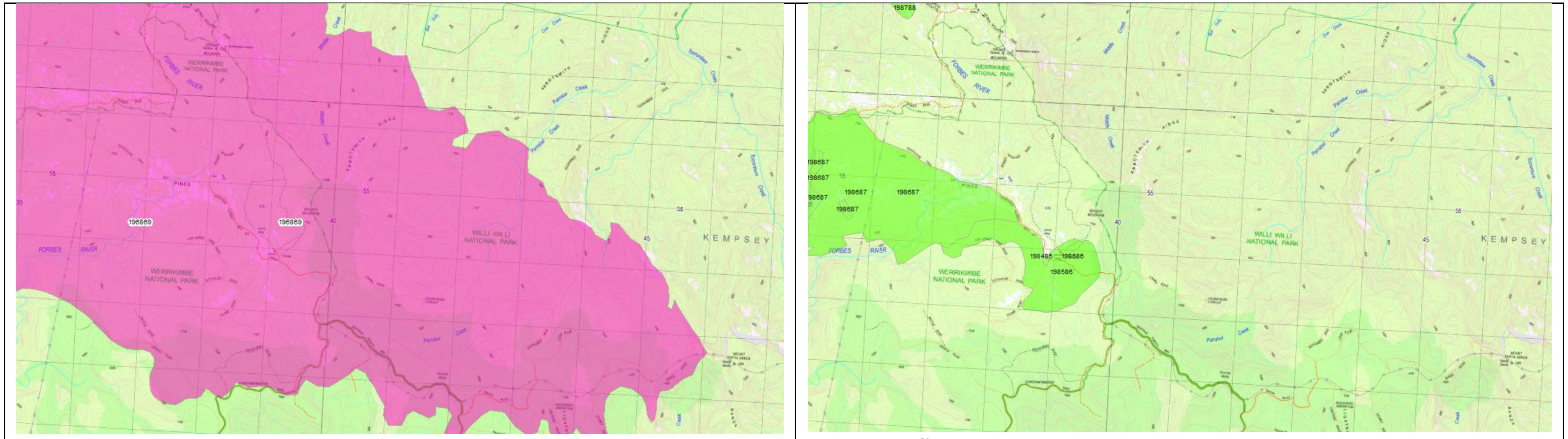


FIGURE 27: EXTRACT FROM WAUCHOPE DISTRICT FIRE CONTROL MAP DATED 1956/57. RAINFOREST IS IDENTIFIED AS GREEN 'SCRUB AREAS INFLAMMABLE UNDER EXTREME CONDITIONS'. SCRUB AND BRUSHWOOD WERE TERMS USED FOR RAINFOREST. SOURCE: FORESTRY COMMISSION OF NSW FIRE PLAN FOR BELLANGRY SUB-DISTRICT (WAUCHOPE DISTRICT) 1957/58 SEASON BELLANGRY SUB-DISTRICT 5TH APRIL 1957. INFLAMMABLE UNDER EXTREME CONDITIONS WAS INTERPRETED IN THE CONTEXT THAT 'SOME FORM OF SHELTERWOOD SYSTEM WILL BE PRACTICED FOR THE BRUSHWOOD STANDS, WHICH WILL BECOME THUS MORE SUSCEPTIBLE TO FIRE'. 'WHERE GULLIES OR CREEKS CONTAIN NARROW BELTS OF MOSTLY UNMERCHANTABLE BRUSHWOODS, THESE AREAS ARE LEFT UNLOGGED IN ORDER TO PROVIDE GREEN FIRE STRIPS WHICH BREAK UP LARGER AREAS OF T.S.I.' (T.S.I. IS TIMBER STAND IMPROVEMENT).

FIGURE 28: STUDY AREA WILDFIRE HISTORY 1964-1967. THE 1960'S WILDFIRES REPRESENT THE EARLIEST KNOWN MAPPING OF WILDIFRES IN THE STUDY AREA. FIRES WERE ASSUMED TO ORIGINATE IN GRAZING LEASES ON RACECOURSE TRAIL AND SPREAD UNDER WESTERLY WIND CONDITIONS TOWARDS THE RAINFOREST STANDS NEAR SPOKES TRAIL AND FURTHER EAST IN THE CATCHMENT OF TOORUMBIE CREEK. THE EXTENT OF THE 1956 MT BOSS FIRE THAT BURNT INTO RAINFOREST IS UNCLEAR ALTHOUGH IT IS REPORTED TO HAVE BURNT MOST OF MT BOSS COMPARTMENT 77.



1968/69 fire season

1986/87 fire season

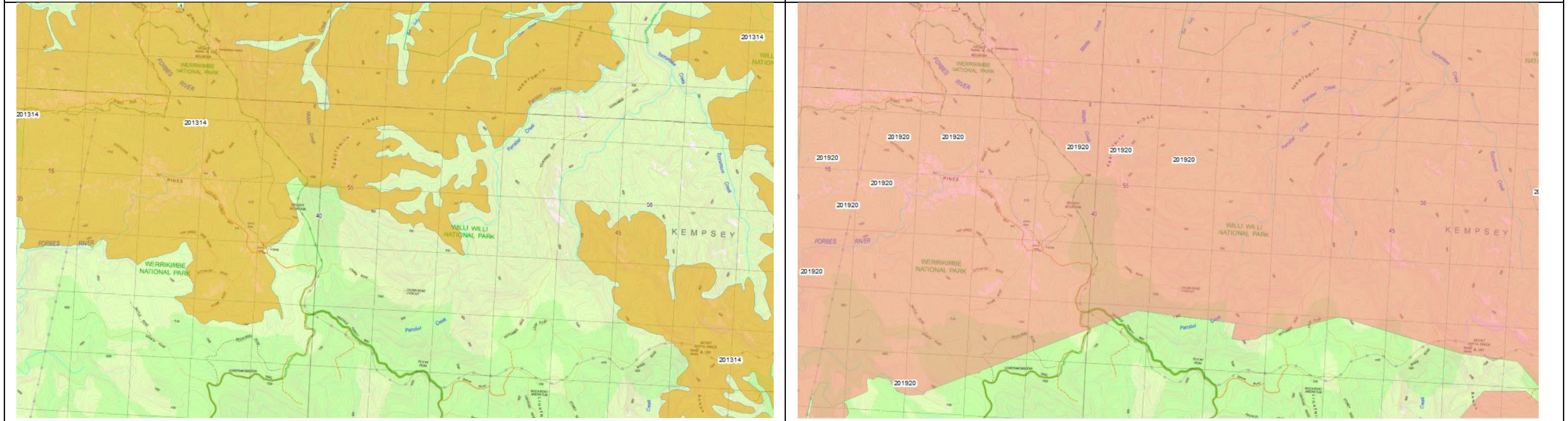
1993/94 fire season

2000/01 fire season

FIGURE 29: STUDY AREA WILDFIRE HISTORY 1968-2001. THE 1960S WILDIFRES ORIGINATING IN THE WESTERN SECTIONS OF WERRIKIMBE NP AND PRIVATE LAND TRAVELLED EAST AND THEIR SHAPE MODIFIED TO REFLECT CHANGING TOPOGRAPHY AND FUELS. EXCEPT UNDER SEVERE CONDITIONS, RAINFOREST STANDS ARE LARGELY PROTECTED IN TOPOGRAPHIC REFUGES.

2001/02 fire season

2012/13 fire season



2013/14 fire season

2019/20 fire season

FIGURE 30: STUDY AREA WILDFIRE HISTORY 2001-2020. THE PERIOD FOLLOWING 2001 SAW THE EMERGENCE OF LARGER FIRE COMPLEXES WHERE THE TRADITIONAL FIRE BEHAVIOUR OF FIRES ORIGINATING IN THE WESTERN SECTIONS OF WERRIKIMBE AND PRIVATE LAND LINKED UP WITH FIRES FROM FORESTS FURTHER NORTH AND EAST. TYPCIALLY THESE FIRES HAD MULTIPLE FRONTS AND FLANKS, EXTENDED SPOTTING DISTANCES OF 2-3 KM AND CONTINUED FOR SEVERAL MONTHS UNTIL WEATHER CONDITIONS AMELIORATED.

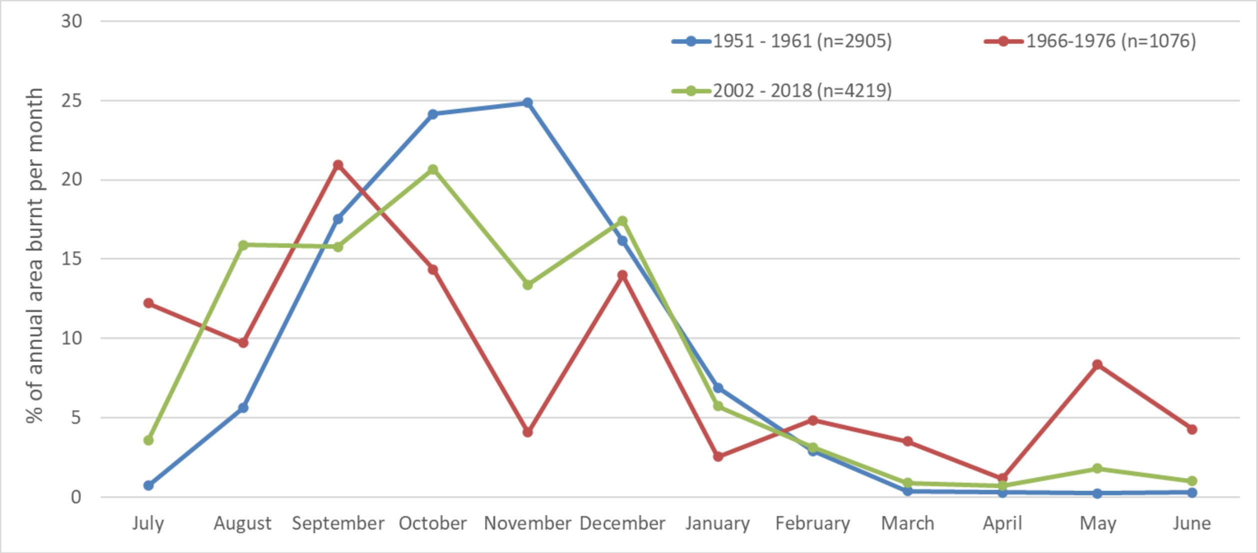


FIGURE 31: PROPORTION OF ANNUAL AREA OF NORTH EASTERN NSW (NORTH OF TAREE) BURNT BY WILDFIRES ACROSS THREE STUDY PERIODS WHERE MAPPING AND DISTRICT SUMMARIES ARE AVAILABLE. THE 1951-1961 PERIOD DATA IS BASED ON FORESTRY COMMISSION OF NSW DISTRICT SUMMARIES, THE 1966-1976 AND 2002-2018 PERIODS ARE BASED ON A NSW RFS WILDFIRE HISTORY MAPPING COMPILATION. N = NUMBER OF WILDFIRE INCIDENTS IN THE SUMMARY PERIOD.

## FIRE BEHAVIOUR IN THE STUDY AREA

The focus for this study is an area that represents a traditional fire path for fires originating from dry lightning storms and accidental or arson ignitions in western sections of Werrikimbe NP and adjacent grazing properties. Fires driven by northern and westerly winds under conditions of spring moisture deficits spread through remote forests and woodlands (Figure 27-30). Major fire runs occur on high (FFDI > 25) to extreme fire danger days, often associated with extreme fire behaviour and damage with crown fires and spotting distances of 3-5 km. When not subject to major runs, the fires can split due to spotting activity (Figure 37) and form separate sectors that can persist for many months. The highest intensity fire behaviour occurs on west-facing slopes and ridges with shrubby scleromorphic understoreys. In the absence of settlements or built infrastructure assets, fires are traditionally monitored and not subject to direct attack. The strategy relies on natural containment provided by the steep topography, rainforest stands, and ameliorating weather. Rainforest stands have been assumed to be inflammable by fire managers (known colloquially as *green fire strips* (Forestry Commission of NSW 1957) since at least the 1950s, although early management plans suggested rainforest stands would become more susceptible to fire following selective harvesting. Rainforest stands continue to be relied upon to provide natural containment options for running fires (Figure 32).

FIGURE 32: NSW NPWS FIRE-FIGHTERS INSTALL A HAND CONTAINMENT LINE IN *BACKHOUSIA SCIADOPHORA* DRY RAINFOREST IN FIFES KNOB NATURE RESERVE AUGUST 17 2019 (IMAGE: NSW NPWS).

The study area straddles the boundary between the undulating NSW northern tablelands and the deeply dissected gorge landforms and eastern escarpment landforms. These landscapes can have a direct impact on fire behaviour. Subsidence associated with synoptic phenomena driving high pressure air systems over the tablelands forces dry warm air to subside on the downwind side of the dissected terrain of the eastern escarpment forming the east flowing catchments of the Hastings and Forbes River tributaries. Many of these tributaries support temperate and sub-tropical rainforest stands.

Air mass subsidence under these conditions can lead to the development of foehn winds. These are associated with rapid variations in fire weather at the onset and end of rising air temperatures, lowering humidity, and increasing wind speeds and mountain turbulence (Sharples et al. 2010). Foehn effects have been described for parts of southeastern Australia (Sharples 2009) with a scenario of partial orographic blocking of relatively moist, low-level air and the subsidence of drier upper-level air in the lee of the mountains. The occurrence of rapid changes in wind speed, temperature and relative humidity at night is one characteristic of a foehn event (Whiteman 2000, Werth et al. 2011). The abrupt transition of conditions that occur with the onset of foehn winds has significant implications for fire fighting (Sharples et al. 2010).

The recurring pattern of fire behaviour in the study area indicates that under severe weather conditions the influence of landscape factors will be reduced and temperate rainforest patches will potentially only be partially protected within their topographic refuges (Figure 33), and rainforest stand edges will be subject to repeated attrition. This phenomenon is consistent with studies elsewhere of the significance of projected increases in severe fire weather (Clarke and Evans 2018; Whetton et al. 2015) on refugia and the effect of extended droughts on drying fuels below critical levels in refugia allowing fires (Figure 45) to encroach (Collins et al. 2019).

FIGURE 33: EXAMPLES OF WILDFIRE DAMAGE TO RAINFOREST MARGINS, WERRIKIMBE NP. THE STAND ON THE LEFT HAS A SHARP BOUNDARY OF FIRE KILLED *EUCALYPTUS OREADES*, THE RIGHT HAS A BOUNDARY OF FIRE DAMAGED AND REGENERATING *EUCALYPTUS CAMPANULATA* FOREST. RAINFOREST TREES ARE SCORCHED FROM RADIANT HEAT IMPACTS FROM THE FIRES IN THE ADJACENT EUCALYPTUS FOREST. THE FIRE TRAVELS FURTHER INTO THE RAINFOREST CONSUMING GROUND LITTER AND

SCORCHING TREE BUTTRESSES AND UNDERSTOREY TREES. THESE UNDERSTOREY FIRE IMPACTS ARE LARGELY UNDETECTED IN REMOTE IMAGERY ANALYSIS. (IMAGES: NSW NPWS)

The relationship between litter fuel moisture content and the corresponding instantaneous soil volumetric moisture content is weakly linear (Figure 34). Soil moisture is a reasonable predictor of litter moisture; however, the temporal relationship is confounded by sampling fuel through the profile, which is likely to absorb and release moisture at different rates to the surface litter exposed directly to the boundary layer conditions.

Mean litter fuel moisture content differed significantly between *Eucalyptus* forest and adjacent rainforest measured at the same time [F(1,333) = 31.63, p<0.001]. The difference in fuel moisture content between these forest types has implications for fuel flammability, heat release, rate of spread, and consumption across rainforest-eucalypt forest boundaries.

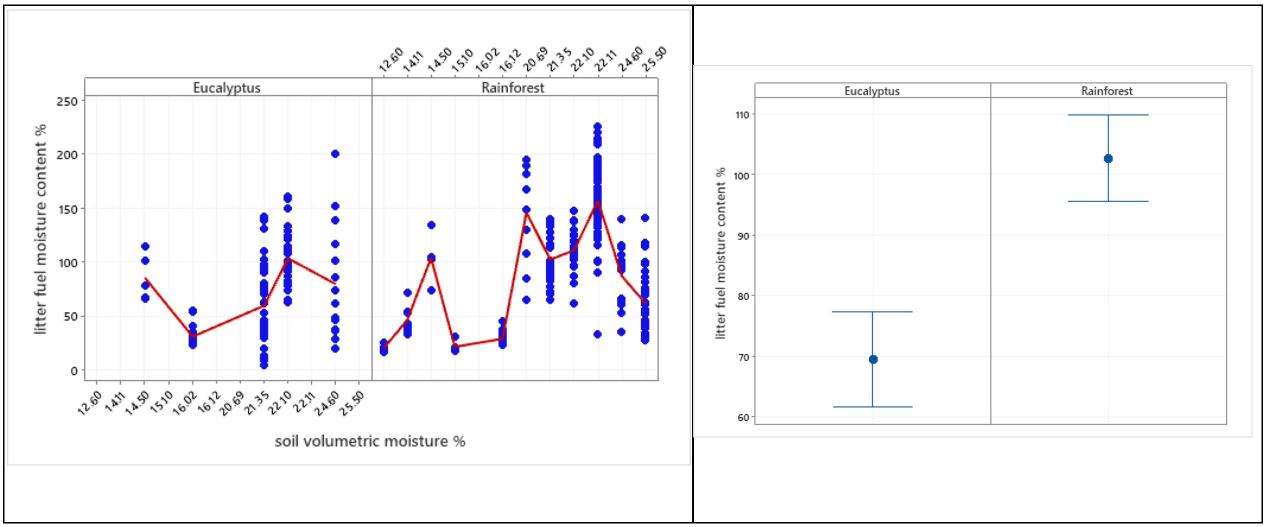


FIGURE 34: FUEL MOISTURE AND INSTANTANEOUS SOIL MOISTURE CONTENT OF PAIRED SAMPLES OF RAINFOREST AND ADJACENT EUCALYPTUS FOREST AT WERRIKIMBE AND WILLI NP.

FIGURE 35 LOW INTENSITY FIRE WITHIN COOL TEMPERATE RAINFOREST, WERRIKIMBE NP 2013. FUEL MOISTURE CONTEXT WAS 20.1 % AND FLAME HEIGHTS < 1 M. WITH A FUEL MOISTURE CONTENT OF 20.1% THE FINE FUELS DID NOT READILY PROPAGATE THE FIRE RUN (IMAGE: ROSS PEACOCK)

FIGURE 36: TYPICAL SPOTTING BEHAVIOUR OF WILDFIRES IN THE STUDY AREA. SPOTTING DISTANCES OF 2-3 KM ARE COMMON. RIDGES TOPS AND SPURS IGNITED AND BURNT PART WAY DOWNSLOPE. BULLS CREEK SECTOR WERRIKIMBE NP 2013. (IMAGE: ROSS PEACOCK).

FIGURE 37: TYPICAL SPOTTING CHARACTERISTIC OF WILDFIRES IN THE STUDY AREA, WALTERS TRAIL KEMPSEY AUGUST 2019. THE FIRE IS BURNING TOWARDS RAINFOREST (IMAGE: NSW RFS).

FIGURE 38: SKINK TRAIL 2 WILDFIRE TRAVELLING DOWNSLOPE TOWARDS TEMPERATE RAINFOREST, OCTOBER 2017. THE FIRE IS BURNING THROUGH DRY PROFILE FUELS OF BRUSHBOX AND WAS CHALLENGING TO CONTAIN WITH AVIATION RESOURCES (IMAGE: ROSS PEACOCK)

FIGURE 39: SKINK TRAIL 2 WILDFIRE OCTOBER 2017 TRAVELLING DOWNSLOPE TOWARDS TEMPERATE RAINFOREST. THE PROGRESSION OF THE FIRE IS CONTAINED BY DENSE *CISSUS HYPOGLAUCA* VINE COVER ON RAINFOREST MARGIN (IMAGE: ROSS PEACOCK)

## RAINFOREST FUEL BIOMASS AND DYNAMICS

Rainforest fuel characteristics in Australia are relatively poorly known. Rainforest fuel components do not feature prominently in the fire behaviour (see review by Watson 2012) or flammability literature. Few accounts of litter dynamics in this forest type are available that have recorded inputs beyond two years, or which address seasonal and annual variability.

A range of long-term studies on litterfall dynamics, decay, and flammability are being conducted in northern NSW to improve our understanding of fuel biomass and hazard dynamics in rainforests and their climatic drivers. In these studies, fuel biomass is typically expressed at tonnes/ha, and fine fuel inputs as g/m2 or kg/ha/year or kg/ha/month. The units of measurement are directly comparable using a conversion factor (1000 g/m2 = 10 tonnes/ha). Rainforests in the study area have relatively low fuel biomass (9-11 t/ha, Table 9), limited near surface and elevated fuels, no ladder fuels, high turnover, and low input rates relative to *Eucalyptus* forests (Table 9). Mean fine fuel depth in rainforest is 21 mm and in 30 mm in *Eucalyptus* forest (Figure 40). Mean coarse fuel mass in rainforest is 5.41 t/ha-(Figure 36). Mean fuel biomass differs significantly between Eucalyptus forest and adjacent rainforest (Figure 40, [F(1,432) = 16.71, p<0.001]. Barker (1992) suggested the low fuel biomass and differential flammability residence time between in East Gippsland (Victoria) cool temperate rainforest (12 t/ha) compared to adjacent *Eucalyptus* forest (15-16 t/ha) explained the dynamic balance in fire behaviour between these forest types.

TABLE 9: RAINFOREST AND EUCALYPTUS FUEL MASS COMPONENTS, NORTHERN NSW. SOURCE: NSW RFS

| | Surface t/ha | Elevated t/ha | Bark t/ha | Canopy t/ha | Total t/ha |
|---|---|---|---|---|---|
| Rainforest | 9.0 | 1.0 | 0.3 | 1.3 | 11.6 |
| Eucalyptus forest | 15.9 | 1.6 | 1.3 | 5.1 | 23.9 |

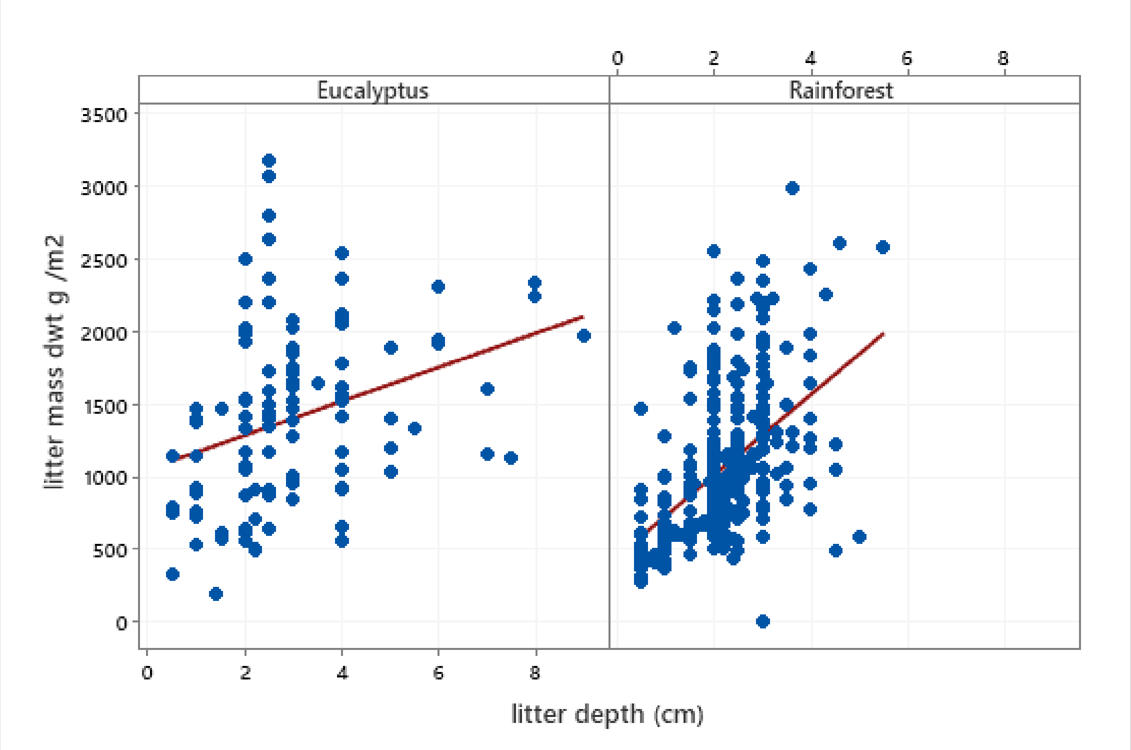


FIGURE 40: NORTHERN NSW COOL TEMPERATE RAINFOREST AND ADJACENT WET SCLEROPHYLL (SHRUBBY) FINE FUEL MASS AND DEPTH. MEAN MASS IN EUCALYPT FOREST IS 1417 G/M2 (95% CI 1306-1528) AND 1143 G/M2 (95% CI 1072-1214) IN RAINFOREST. DATA BASED ON DESTRUCTIVE SAMPLING (N=434)

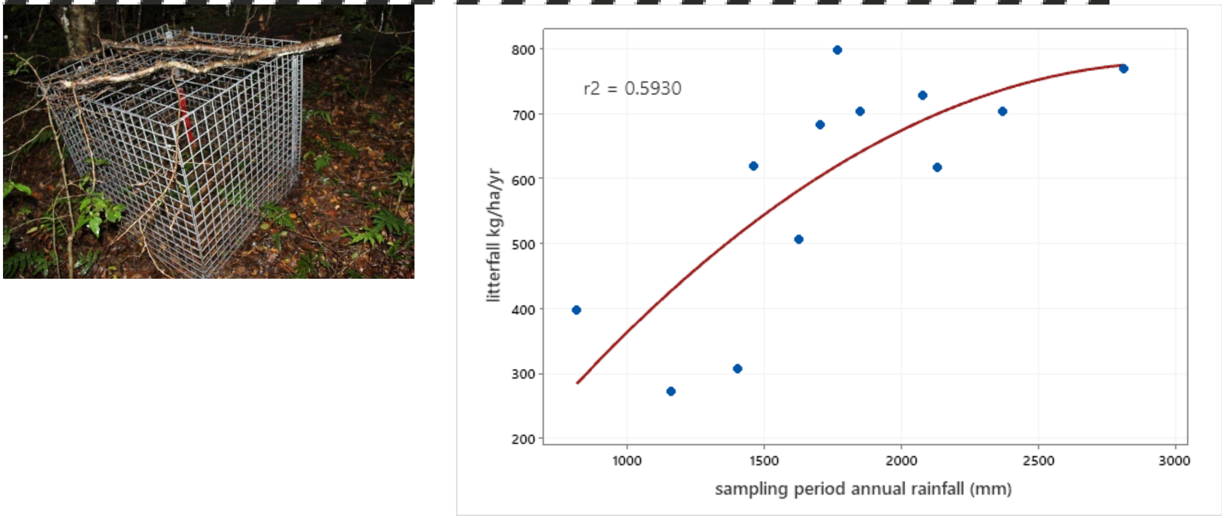


FIGURE 41: COARSE FUELS (> 25 MM) ARE MONITORED ANNUALLY ACROSS A SERIES OF COLLECTING STATIONS IN WERRIKIMBE AND WILLI WILLI NP. COARSE FUELS ACCUMULATE AT AN AVERAGE RATE OF 590 kg/yr$^{-1}$/ha$^{-1}$. TOTAL INPUTS OF COARSE FUELS ARE CLOSELY RELATED TO TOTAL ANNUAL RAINFALL. DATA REPRESENTS THE 2009-2020 PERIOD (IMAGE: ROSS PEACOCK).

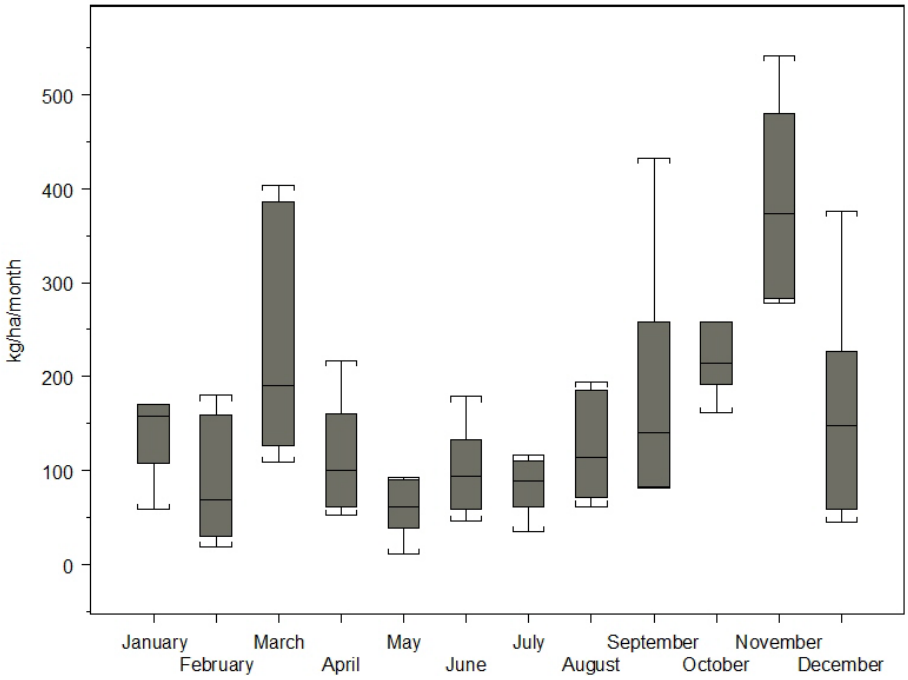


FIGURE 42: SEASONAL VARIATION IN FINE FUEL ACCUMULATION. INPUTS VARY WITH SEASONAL CONDITIONS, PEAKING WITH THE SPRING GROWTH PERIOD FOR MOST RAINFOREST CANOPY TREES, AND REACHING A MINIMUM IN WINTER.

Fuel accumulation in rainforest is strongly seasonal (Figure 42), peaking in spring with annual growth flush of *Nothofagus* (October-November) and *Ceratopetalum*. These trends are largely driven by inputs from *Nothofagus* (29.6%) and *Ceratopetalum* (24.9%), which together represent the bulk of the leaf litter mass on the rainforest floor.

Canopy leaf litter is most flammable when relatively fresh in the first 2.5 months after litter fall. Leaf abscission associated with the flush of 8-10 new leaves per stem is assumed to result in the peak leaf fall each November. The rainforest litter bed should therefore be most combustible in the spring of each year which is the peak fire season in northern NSW. The maximum available fine fuel in rainforests is therefore mid-spring, which is also the season of highest soil and fuel moisture deficits and, in northern NSW, dry lightning storm activity.

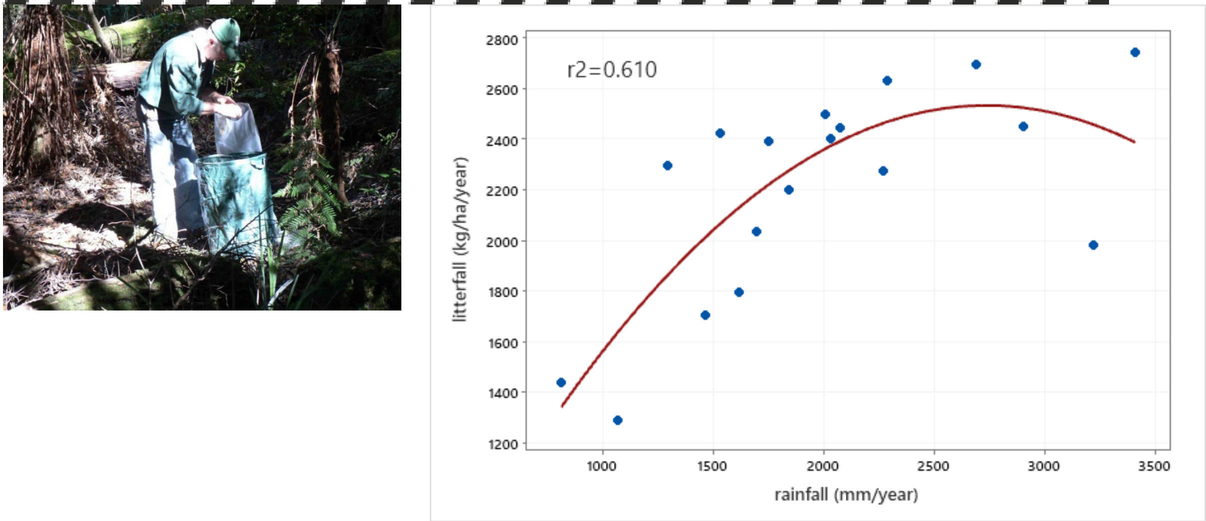


FIGURE 43: FINE FUELS ARE MONITORED MONTHLY ACROSS A SERIES OF COLLECTING STATIONS IN WILLI NP. FINE FUELS ACCUMULATE AT AN AVERAGE RATE OF 784 kg/yr-/ha. TOTAL INPUTS OF FINE FUELS ARE CLOSELY RELATED TO TOTAL ANNUAL RAINFALL. (IMAGE: ROSS PEACOCK).

Annual litterfall and annual rainfall are significantly ($p<0.001$) and positively correlated with 60.1% of the variation in annual litterfall being explained by the quadratic regression model [Figure 43, $F(1,17) = 11.29$, $p<0.001$]. When rainfall increases fine litterfall (Figure 43) and course litterfall both increase (Figure 41).

Post-fire litterfall dynamics differ between rainforests and *Eucalyptus* forests on the north coast (Figure 45-46). Rainforests accumulate their post-fire litter mass more rapidly than *Eucalyptus* forests, primarily due to the large mass of sub-canopy tree scorch in rainforest and the resulting post-fire leaf fall. A typical low-intensity understorey fire in rainforest will result in new post-fire litter mass exceeding the levels prior to the fire (Figure 45). In contrast, a wildfire of similar intensity in a *Eucalyptus* forest will see a significant reduction in litter mass (Figure 46).

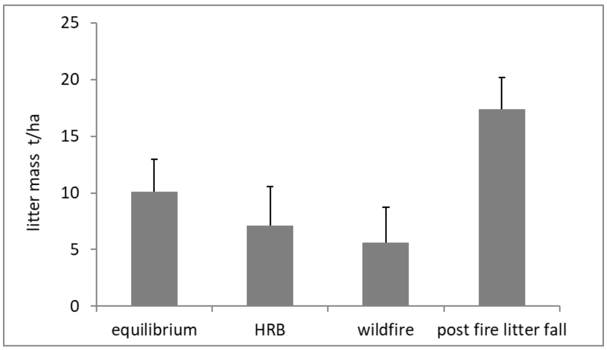


FIGURE 45: CHANGES IN MEAN FINE FUEL LITTER MASS OF *NOTHOFAGUS-CERATOPETALUM* RAINFOREST AT WERRIKIMBE NP FROM THE EQUILIBRIUM STATE, IMMEDIATELY FOLLOWING HAZARD REDUCTION BURNING (HRB), WILDFIRE AND THE IMMEDIATE POST WILDFIRE LITTER FALL EVENT.

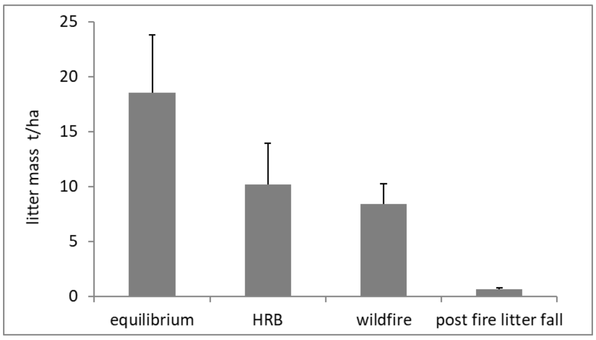


FIGURE 46: CHANGES IN MEAN FINE FUEL LITTER MASS OF TABLELAND *EUCALYPTUS CAMPANULATA* FOREST AT WERRIKIMBE NP FROM THE EQUILIBRIUM STATE, IMMEDIATELY FOLLOWING HAZARD REDUCTION BURNING (HRB), WILDFIRE AND THE IMMEDIATE POST WILDFIRE LITTER FALL EVENT.

Post-fire fuel mass dynamics are normally expressed as the relationship between fuel load (t/ha) and time using a negative exponential model such as the Olsen curve. Typically, surface fuels (i.e., fine litter) receive the most attention from researchers and fire-behaviour modellers due to their role in igniting the fuel complex. Surface fire intensity is an important indicator of the likelihood that a crown fire will ignite, which, in turn, defines the limits of suppression capability (Gould and Cruz 2012). A projected Olsen curve for cool temperate rainforests, based on locally derived parameters for the decay constant *k* and the initial post-fire litter mass, is presented in Figure 47. Fuel mass is predicted to reach equilibrium mass approximately eight years after a fire.

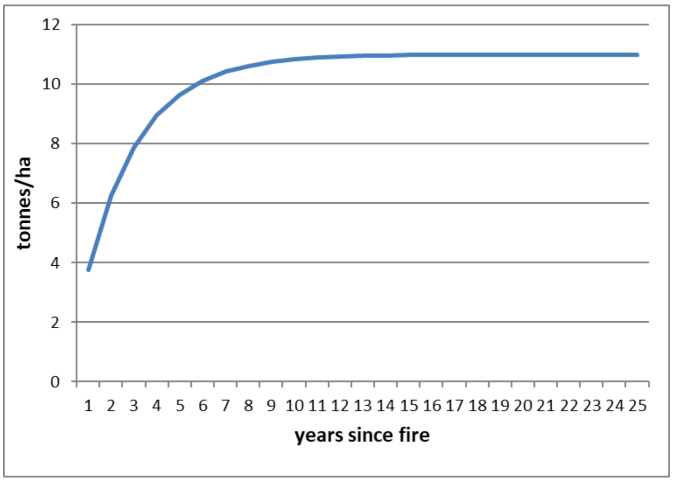


FIGURE 47: QUANTITY OF FUEL LITTER ACCUMULATION MODELLED USING THE OLSEN CURVE. A DECAY CONSTANT OF 0.42 IS BASED ON LOCAL LITTER DECOMPOSITION EXPERIMENTATION. THE INITIAL POST-WILDFIRE LITTER MASS IS SET AT 3.7 T/HA BASED ON LOCALISED SAMPLING.

The NSW north coast fire season typically runs from October to January. Where a spring drought is experienced with deep fuel profile drying, fuel moisture may fall below the critical threshold of approximately 10-20% (Figure 48). This permits the ignition of ground fuels within rainforests normally considered fire resistant refugia. Eleven years of continuous monitoring of soil moisture within rainforests at Willi Willi NP has demonstrated a critical threshold for litter fuel moisture ignition and its capacity to carry a ground fire (Figure 48).

When soil volumetric moisture content approaches 10-20%, usually following a period of drying extending over several months, a landscape-level wildfire in one of the adjoining national parks (Werrikimbe and Oxley Wild Rivers) was in each case recorded. These were wildfires where rainforest patches were burnt. Deep drying of the litter profile was a key contributing factor to the widespread wildfires in Victoria in 2009 (Cawson et al. 2020). In Tasmania, *Nothofagus* rainforest is only able to sustain fire at times of the year when the total rainfall in the preceding month has been less than 50 mm (Styger 2014, Styger and Kirkpatrick 2015)

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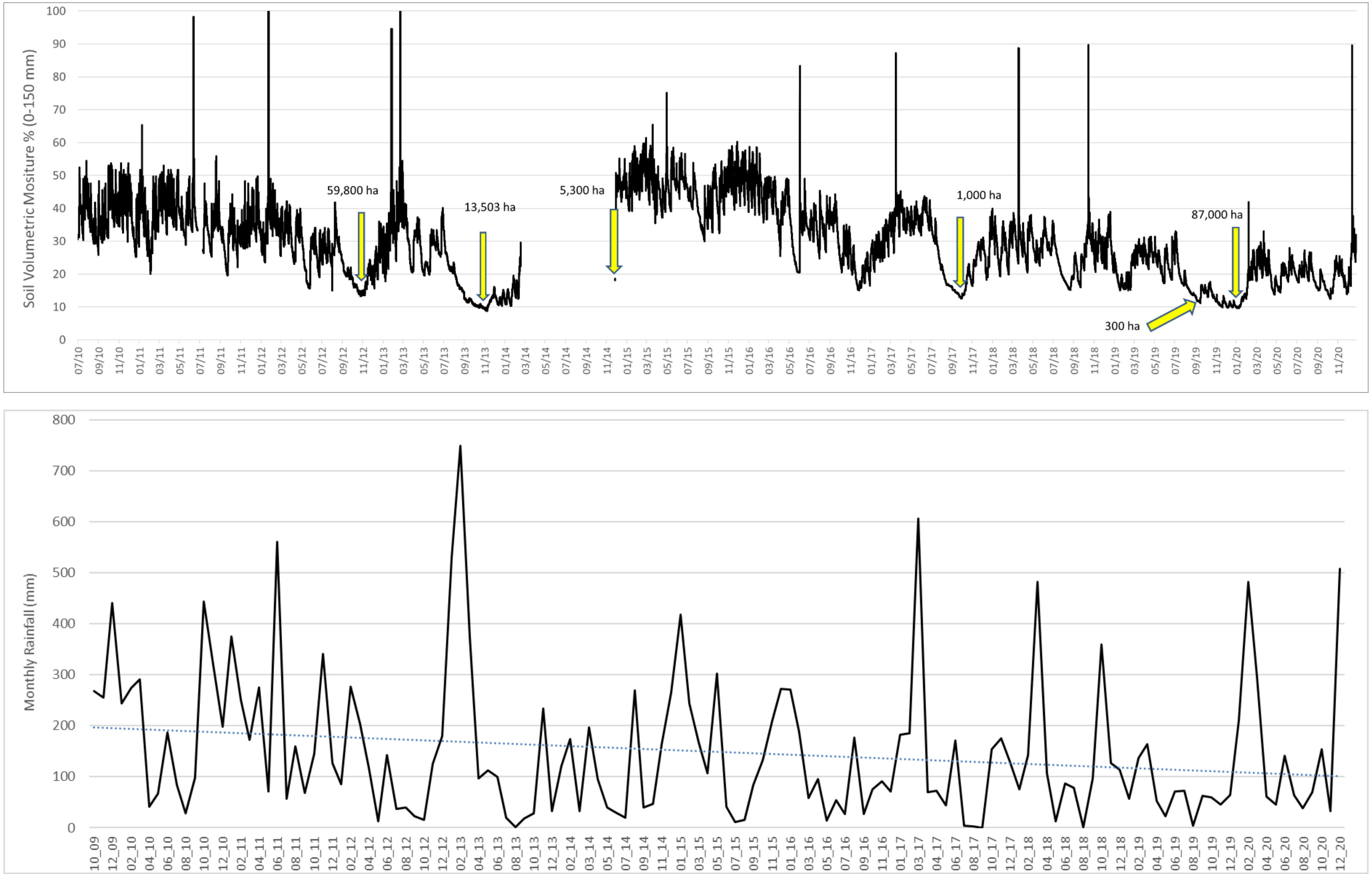

FIGURE 48: DECADAL PATTERN OF CLIMATE VARIABILITY WERRIKIIMBE NP NORTHERN NSW BASED ON LOCAL OBSERVATIONS. SOIL VOLUMETRIC MOISTURE IS MEASURED WITH A SINGLE SENSOR IN RAINFOREST AND DATA CAPTURED EVERY30 MINUTES, RAINFALL IS ALSO CAPTURED ON THE SAME TIME SCALE AND IS SUMMARISED AS MONTHLY RAINFALL. EACH MAJOR FIRE EVENT THAT INVOLVED SOME INCURSION INTO RAINFOREST IS IDENTIFIED WITH THE TOTAL EXTENT OF THE FIRE IN HA, INCLUSIVE OF RAINFOREST AND OTHER VEGETATION COMMUNITIES. ASSUMING HYDROSTATIC EQUILIBRIUM, SOIL MOISTURE AND FUEL MOISTURE CONTENT WILL REACH AN EQUILIBRIUM MOISTURE CONTENT IF THE FUEL IS EXPOSED TO CONSTANT ATMOSPHERIC CONDITIONS OF TEMPERATURE AND HUMIDITY FOR AN INFINITE LENGTH OF TIME. THE EXTENDED DRYING PERIOD FROM SEPTEMBER 2019 WOULD HAVE RESULTED IN DEEP LITTER PROFILE DRYING. LARGE WILDFIRES IN THE STUDY AREA ARE ASSOCIATED WITH PROLONGED SPRING SEASONAL DROUGHTS AND DEEP PROFILE FUEL DRYING

## REMOTELY SENSED FIRE SEVERITY

The extent of fire impacts on the Gondwana Rainforests in 2019/20 can be estimated using a range of spatial data products. The traditional approach is to use the NSW Rural Fire Service end of season wildfire extent product (RFS ICON), which compiles and validates a season's individual fire incident maps into a statewide product. The 2019/20 season, however, provided three alternate approaches to delineating wildfire extent. FESM (Gibson et al. 2020) provides a map of fire extent and severity, based on Sentinel 2 with extensive model training, adjustment, and validation for individual fires and vegetation communities. An ensemble learning algorithm (Random Forest) is used to classify pixels with an iterative approach ensuring a convergence to classification problems. GEEBAM (Google Earth Engine Burnt Area Map, NSW Department of Planning, Infrastructure and Environment 2020d) also relies on Sentinel 2 imagery to calculate the difference between the Normalized Burn Ratio (NBR) before and after a fire, although thresholds of severity are manually interpreted based on the difference between pre- and post-fire values of the NBR. The third product is RAFIT (Rapid Assessment of Fire Impact on Timber, Forestry Corporation of NSW 2020, Forestry Corporation of NSW (2020b), an NBR differential product using the Google Earth Engine data catalogue which was field tested for accuracy by Forestry Corporation field staff. The RAFIT product has a significant advantage in any temporal analysis in being able to be generated using Google Earth Engine for a user-defined time series, which allows any particular area to have a wildfire impact date determined within an approximately seven-day window. The challenge with each product is how the ΔNBR value adjusts for changes in canopy reflectance due to factors such as drought, and how effective it is in assessing fire severity for understorey fires in rainforest. For this study, the FESM product was used to evaluate the relationship between fire severity and changes in rainforest condition, and the RAFIT product was used to calculate the fire impact dates. Once the dates for the wildfire impacts were established using RAFIT, the relationship to the continuously monitored environmental variables and NSW RFS instantaneous fire weather data was examined.

The relationship between fire severity observed for individual rainforest trees (Table 10) within fixed-area plots and the Sentinel 2 fire severity measure was examined by intersecting the fixed-area plot with a 15m radius buffer for the remotely sensed raster product. While the remotely sensed product was not designed to have sufficient precision to identify fire severity effects at the scale of individual trees, the relationship is nonetheless highly significant (overall accuracy 0.6100, unweighted Kappa statistic 0.4117, McNemar's test $p < 0.001$). The Kappa statistic is a measure of agreement between the modelled fire severity class and observed fire severity class on each tree relative to what would be expected by chance.

At a landscape level, the remotely sensed fire severity classification performs well at predicting the relative proportion of trees exhibiting a fire severity response at the forest stand level, despite the challenges of detecting understorey fires in rainforest by remote sensing where the impacts on canopy tree health can be delayed or obscured by the multiple tree strata.

TABLE 10: CONFUSION MATRIX AND KAPPA BALANCED ACCURACY STATISTIC FOR THE FESMV3 MODEL AND VALIDATION DATA CONSISTING OF FIELD OBSERVED FOLIAGE AFFECTED ON 1554 INDIVIDUAL TREES WITHIN THOSE PLOTS.

| | **Directly observed fire severity class (individual tree scale) based on % of canopy scorched or consumed** | | | | | |
|---|---|---|---|---|---|---|
| **Remotely sensed fire severity class using the averaged pixel scale (FESMv3) based on reflectance and fractional cover indices** | Extreme Severity | High Severity | Moderate Severity | Low Severity | Unburnt | Balanced accuracy |
| Extreme Severity | | 10 | 17 | 4 | 0 | na |
| High Severity | | 51 | 45 | 7 | 0 | 0.7451 |
| Moderate Severity | | 7 | 144 | 95 | 0 | 0.6286 |
| Low Severity | | 0 | 232 | 84 | 0 | 0.5633 |
| Unburnt | | 0 | 142 | 66 | 650 | 0.8788 |
| Total number of trees | 0 | 68 | 580 | 256 | 650 | 1554 |

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FIGURE 49: UNDISTURBED *NOTHOFAGUS MOOREI* TEMPERATE RAINFOREST. THE MULTIPLE STRATA CREATE A DENSE SHADED UNDERSTOREY OF GROUND FERNS, CLIMBERS AND SHRUBS (IMAGE: ROSS PEACOCK)

FIGURE 50: LOW-INTENSITY FIRE IN *NOTHOFAGUS MOOREI*-DOMINATED TEMPERATE RAINFOREST. FINE FUELS AND LIVE GROUND VEGETATION ARE CONSUMED AND SCORCH HEIGHTS ARE < 2M. TALL SHRUBS AND UNDERSTOREY TREES ARE SCORCHED LEADING TO IMMEDIATE POST-FIRE LITTERFALL. (IMAGE: ROSS PEACOCK)

FIGURE 51: MODERATE-INTENSITY FIRE IN *NOTHOFAGUS MOOREI*-DOMINATED TEMPERATE RAINFOREST. SCORCH HEIGHTS EXCEED 10M, WITH OCCASIONAL CANOPY SCORCH AND TREE COLLAPSE. THE UNDERSTOREY HAS BEEN LARGELY CONSUMED (IMAGE: ROSS PEACOCK)

FIGURE 52: MODERATE TO HIGH INTENSITY FIRE IN *NOTHOFAGUS MOOREI*-DOMINATED TEMPERATE RAINFOREST. SCORCH HEIGHTS EXCEED 10M, FIRES COMMONLY REACH INTO TREE CANOPIES AND TREE COLLAPSE IS WIDESPREAD (IMAGE: ROSS PEACOCK)

## IS THERE A SPECIFIC SUB-POPULATION OF RAINFORESTS THAT ARE MORE LIKELY TO BE BURNT?

Rainforest stands can be segregated into sub-populations based on characteristics such as their basal area distributions. Each reflects historical differences in growth stage, canopy condition, and previous levels of disturbance. The vulnerability to ignition of rainforests with different stand characteristics, based on their basal area distributions, was examined in the Hastings-Macleay study area using data from 55 long-term growth plots in Werrikimbe and Willi Willi National Parks. These plots describe the unburnt reference state prior to the 2019/20 wildfire season. In the unburnt state, stand basal areas had a mean basal area of 76 m$^2$/ha.

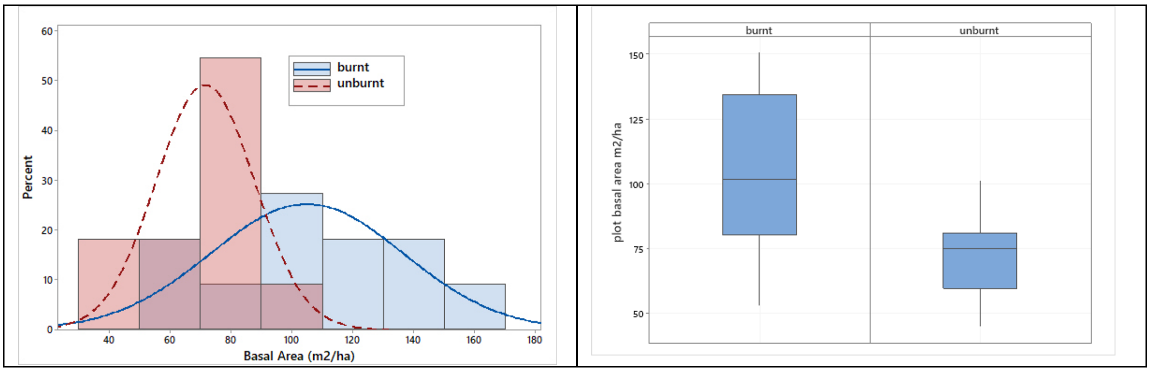


FIGURE 53: IMPACTS OF WILDFIRE ON RAINFOREST STRUCTURE. BASED ON A REGIONAL INVENTORY OF FIFTY-FIVE LONG-TERM GROWTH PLOTS (LEFT), ELEVEN WERE RANDOMLY SELECTED AND COMPARED TO THE ELEVEN BURNT PLOTS IN THE SAME REGION (RIGHT). BURNT RAINFOREST WAS CHARACTERISED BY SIGNIFICANTLY GREATER STAND BASAL AREAS THAN AREAS THAT DID NOT BURN DURING THE SAME WILDFIRE EVENT.

To determine if there was a specific sub-population of rainforests that are more likely to be burnt the stand basal areas of the 11 burnt samples were compared with a randomly selected sample of 11 of the 55 unburnt reference state samples. There is a significant difference in mean values for stand basal area (m2/ha) between rainforest stands that burnt and those that did not [One-way ANOVA, F(1,20) = 9.71, p=0.005]. Mean basal area (Figure 53) was 105.1 m2/ha (95% CI 89.3, 120.9) for burnt stands and 71.7 m2/ha (95% CI 55.9, 87.5) for unburnt stands. The analysis assumes that all plots have an equal probability of burning and that there is not a correlation between plot basal area and the position of those stands relative to the fire runs. All stands are therefore assumed to have equal exposure to ignition from ember attack. The analysis suggests that stands with more biomass, particularly of larger trees, are better at capturing embers and providing a dry fuel source. Mean tree diameter (Figure 54) in burnt stands was 30.8 cm (95% CI 29.1, 32.5), and in unburnt stands 21.4 cm (95% CI 19.9, 22.9). The differences are significantly different (one-way ANOVA, p<0.001).

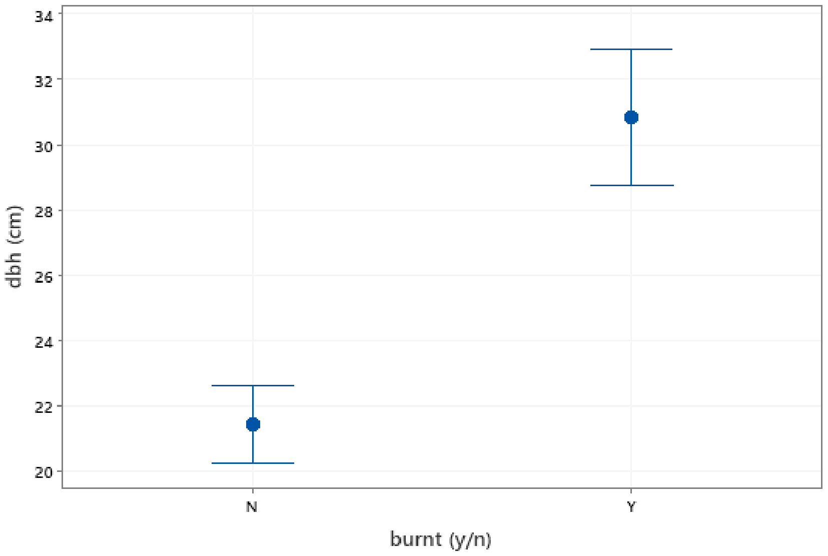


FIGURE 54: BURNT RAINFOREST WAS CHARACTERISED BY SIGNIFICANTLY LARGER MEAN TREE DIAMETERS THAN UNBURNT RAINFOREST AFTER THE SAME WILDFIRE EVENT.

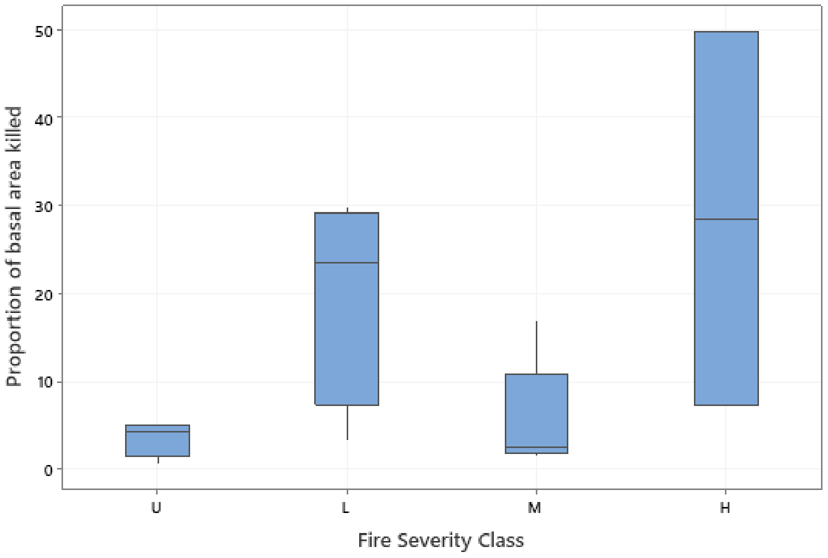


FIGURE 55: PROPORTION OF STAND BASAL AREA KILLED BY FIRE ACCORDING TO EACH REMOTELY SENSED FIRE SEVERITY CLASS [ U (UNBURNT), L (LOW), M (MODERATE) AND H (HIGH].

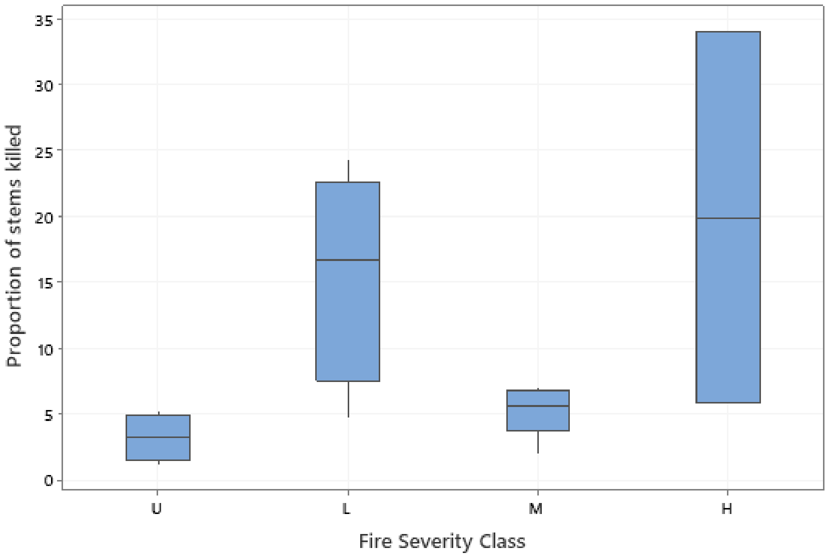


FIGURE 56: PROPORTION OF TREE STEMS KILLED BY FIRE ACCORDING TO EACH REMOTELY SENSED FIRE SEVERITY CLASS [ U (UNBURNT), L (LOW), M (MODERATE) AND H (HIGH].

There is no significant difference [one-way ANOVA F(3,14) = 3.11, p=0.071] in the proportion of basal area killed amongst the different plot-scale fire severity classes (Figure 55). This suggests that the remotely sensed fire severity classes in themselves are not a good predictor of the proportion of tree biomass being killed by the fire, and potentially other factors at the individual tree level may be more relevant. There is a weakly significant trend however for the proportion of trees killed (Figure 56, one-way ANOVA F(3,14) = 3.62, p=0.049].

The distribution of the tree diameter size classes which survived wildfire or died is broadly similar across the four remotely sensed fire severity types (Figure 57). A weak trend of increasing proportions of larger diameter trees exhibiting mortality exists for the low and moderate severity classes.

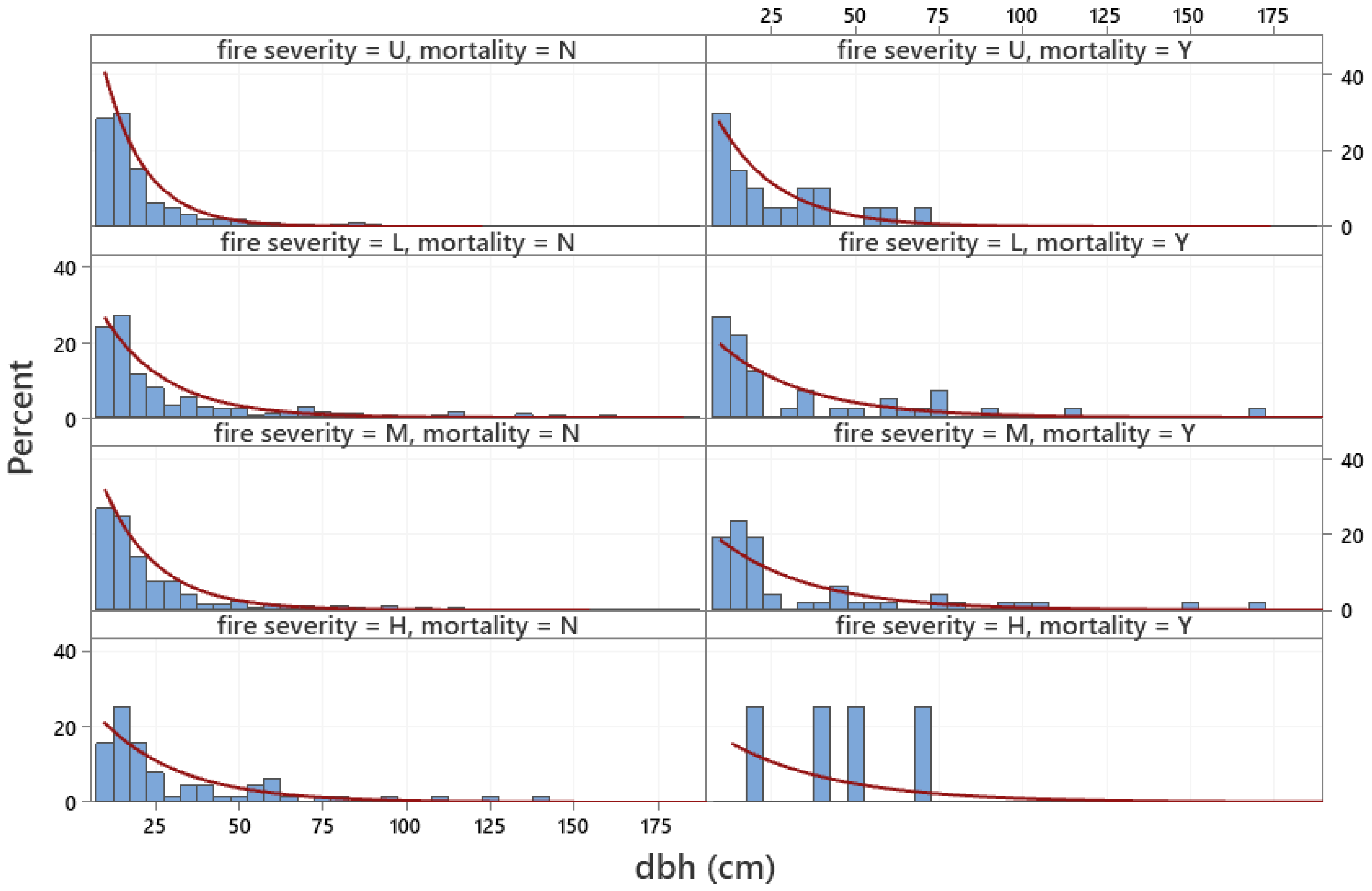


FIGURE 57: THE DISTRIBUTION OF TREE DIAMETERS ACROSS THE VARIOUS REMOTELY SENSED FIRE SEVERITY CLASSES [ U (UNBURNT), L (LOW), M (MODERATE) AND H (HIGH] AND THE STATUS (DEAD OR SURVIVING) OF INDIVIDUAL TREES POST-FIRE. A 2-PARAMETER EXPONENTIAL MODEL IS FITTED TO EACH DISTRIBUTION. EACH DISTRIBUTION IS RIGHT SKEWED WITH AN INCREASED PROPORTION OF DEAD TREES IN THE LARGER DIAMETER CLASSES. IN EACH PANEL. THE DISTRIBUTION OF TREE DIAMETER CLASSES AND POST-FIRE SURVIVAL IS BROADLY SIMILAR ACROSS THE REMOTELY SENSED FIRE SEVERITY CLASSES.

## INTERSPECIFIC PATTERNS OF TREE POST-FIRE REGENERATION

Post-fire regeneration strategies for northern NSW temperate rainforest tree species predominantly rely on basal resprouting, with a smaller contribution from stem sprouting (Clarke et al. 2009, 2015). Rainforests lack a persistent soil seedbank (Clarke et al. 2015) and post-fire seedling recruitment is relatively uncommon (Campbell and Clarke 2006). Resprouting in *Nothofagus* is an effective strategy for rainforest trees to maximize occupancy, preserve their genetic diversity (Premoli et al. 2008) and minimize turnover. This is particularly relevant to a monoecious wind-pollinated species such as *Nothofagus moorei* (Read and Hill 1985), which demonstrates masting behaviour infrequently, around three times per decade, and continuously resprouts from basal meristematic tissue. The species also lacks mechanisms to store seed in the canopy or soil, and seed viability is limited to around seven days. Where seedlings are recruited and persist as saplings, they are observed primarily in gaps such as clearings and road edges. *Nothofagus* seedlings will recruit following low-intensity patch fires provided the overstorey trees are maintained (Hill and Read, 1984), the intensity of the fire is not great (Barker 1991), or there is a viable seed crop available (Hill 1982). This strategy is in contrast to the more widespread sclerophyllous vegetation, which typically has all or most of the aboveground biomass consumed or killed and regenerates from canopy-stored or soil-stored seed banks. Despite the fact that resprouting is a key functional trait used in studies of community assembly and persistence following fire (Clarke et al. 2012), studies documenting resprouting behaviours in temperate rainforests are uncommon. This lack of information constrains the development of models of resilience and persistence in the temperate rainforests of northern NSW.

Interspecific trends in post-fire regeneration strategies across the rainforest tree species in the study area indicate a clear predominance of resprouting behaviours (Table 10). Across all tree species, 77.3% of individual tree stems >10 cm DBH that showed evidence of direct fire impacts (e.g. stem charring) exhibited coppicing behaviour (either basal, stem, or canopy). Basal coppicing was the most frequent behaviour observed. Seedling regeneration within six months of the fire was infrequent, and largely restricted to a small number of families (e.g. Myrtaceae and Proteaceae) and included genera that occur infrequently in rainforest (e.g. *Eucalyptus*, *Banksia*, *Persoonia*).

During the 2019/20 wildfire season, *Nothofagus moorei* produced moderate quantities of seed in December 2019 (mean 189 seeds/m$^2$) leading to infrequent seedling persistence. The December 2020 masting season however resulted in a much higher seed rain (mean 7751 seeds/m$^2$), an average germination of 11.48% and a seedling density of 140/m$^2$ at the two and three leaf pair stage in April 2021 (Figure 57).

FIGURE 57: NOTHOFAGUS MOOREI POST-WILDFIRE SEEDLING RECRUITMENT, WILLI WILLI NP APRIL 2021. SEEDLINGS AT TWO-THREE LEAF PAIRS EIGHTEEN MONTHS POST-GERMINATION.

TABLE 10: RAINFOREST TREE POST-FIRE REGENERATION MODES FOLLOWING NOVEMBER 2019 WILDFIRES. EACH TREE IS ALLOCATED TO THE DOMINANT REGENERATION MODE OBSERVED ALTHOUGH A PROPORTION OF TREES WILL EXHIBIT MULTIPLE REGENERATION BEHAVIOURS. ONLY TREES WITH FIRE SCAR EVIDENCE ARE SUMMARISED.

| **Tree Species** | **Number of burnt tree stems** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **Nil coppice** | **Basal coppice** | **Stem coppice** | **Canopy coppice** | **Total coppicing** | **Seedling** | **Total number of trees observed** | **Proportion of burnt trees exhibiting coppice behaviour** |
| *Elaeocarpus reticulatus* | 0 | 1 | 0 | 0 | 1 | 0 | 1 | 100 |
| *Acacia elata* | 1 | **0** | 0 | 1 | 1 | 0 | 2 | 100 |
| *Banksia integrifolia* | 1 | 0 | 0 | 0 | 0 | 1 | 1 | 100 |
| *Acmena smithii* | 1 | 0 | 0 | 0 | 0 | 1 | 2 | 100 |
| *Eucalyptus obliqua* | 4 | 0 | 7 | 0 | 7 | 0 | 11 | 100 |
| *Cryptocarya meissneriana* | 4 | 2 | 2 | 0 | 2 | 0 | 6 | 100 |
| *Sloanea woollsii* | 1 | 1 | 0 | 0 | 1 | 0 | 2 | 100 |
| *Ackama paniculata* | 10 | 13 | 4 | 2 | 19 | 0 | 29 | 96.6 |
| *Eucalyptus andrewsii* | 8 | 0 | 0 | 0 | 0 | 8 | 8 | 88.8 |
| *Nothofagus moorei* | 96 | 153 | 5 | 2 | 160 | 3 | 256 | 80.7 |
| *Ceratopetalum apetalum* | 101 | 142 | 8 | 26 | 176 | 2 | 277 | 79.1 |
| *Doryphora sassafras* | 14 | 17 | 1 | 2 | 20 | 0 | 34 | 65.3 |
| *Callicoma serratifolia* | 12 | 30 | 1 | 8 | 39 | 0 | 51 | 57.3 |
| *Orites excelsus* | 12 | 0 | 0 | 0 | 0 | 12 | 12 | 57.1 |
| *Persoonia media* | 3 | 0 | 0 | 0 | 0 | 3 | 3 | 42.8 |
| Total number of trees | **267** | 359 | 28 | 41 | **428** | 30 | **695** | **Mean 77.3** |

Monitoring of the post-fire survival of *Nothofagus* seedlings at Werrikimbe and Willi Willi National Parks using permanent plots established within stands burnt in 1994, 2013 and 2019 (Figure 58) is ongoing. Seedling survival post-fire declines rapidly (Figure 59). The majority of seedlings do not persist beyond the dicotyledon stage. Mortality is attributed to shading, competition with ground ferns, leaf litter burial and invertebrate grazing. Survival is enhanced on elevated microsites such as mossy fallen logs and stumps.

FIGURE 58: *NOTHOFAGUS MOOREI* POST-WILDFIRE SEEDLING RECRUITMENT, WILLI WILLI NP APRIL 2021. SEEDLING DENSITY IS MEASURED IN A SERIES OF 0.5M$^2$ PLOTS. (IMAGE: ROSS PEACOCK).

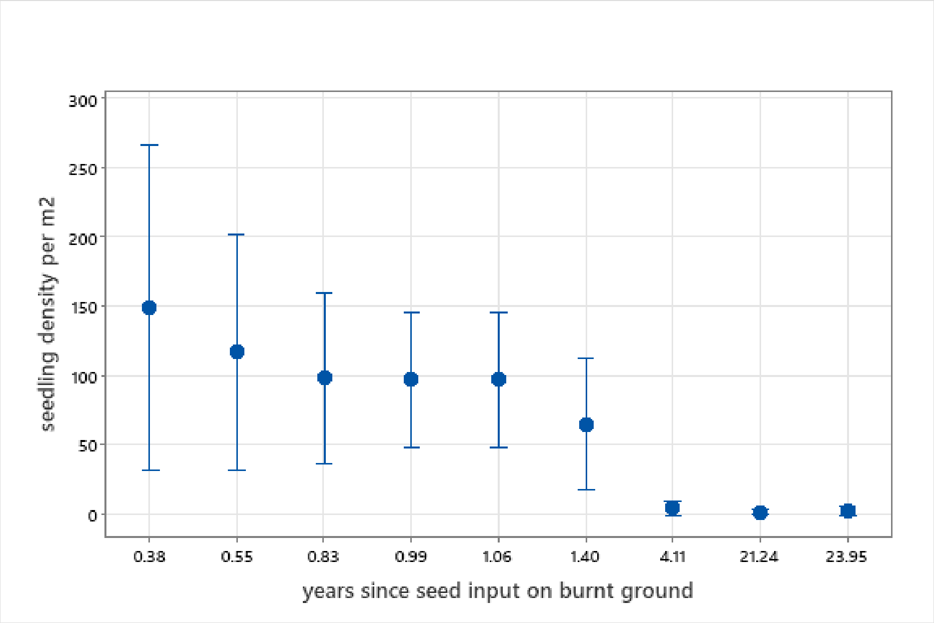


FIGURE 59: *NOTHOFAGUS MOOREI* POST-WILDFIRE SEEDLING DENSITY, WERRIKIMBE AND WILLI WILLI NATIONAL PARKS. SEEDLING CENSUSES POOLED ACROSS WILDFIRES IN 1994, 2013 AND 2019.

## RAINFOREST TREE PRE-EXISTING DAMAGE, IGNITION, AND MORTALITY

At the individual tree level, susceptibility to buttress ignition and post-fire tree collapse (Figure 60) and subsequent post-fire coppice regeneration was examined through population surveys within stands subject to varying intensity of wildfire damage. Pre-existing damage to rainforest trees was recorded as a predictor variable for the probability of ignition and collapse. Pre-existing damage refers to callous, cavity, and hollow formation in the buttresses and lower portions of rainforest trees. While cavities in rainforest trees may be a natural phenomenon resulting from the development of vertical internal decay or heart rot of the tree base (Putz 2013), the eventual formation of larger cavities due to the activities of successive fires and insect and fungal attack will increase the size and susceptibility of the cavity to ember attack or surface fires.

Rainforest tree trunks provide mechanical support and tree hydraulics. It is assumed their resistance to heating is a function of their mass, wood density and moisture content, bark thickness and morphology. Damage occurs when the vascular cambium, positioned just below the bark, is heated to lethal temperatures during contact with the fire-line or from smouldering combustion after the fire line has passed. Tissue necrosis or consumption may occur leading to a loss of mechanical support, reduced hydraulic functioning and callous or wound wood formation. Fire scars, as with all wounds, provide opportunities for infection by wood-inhabiting microorganisms including decay fungi.

Callous or cavity formation from fire reduces the cross-sectional area of xylem sapwood tissue supporting tree hydraulics and can lead to reduced water potential in the crown (Rundel 1972). The cavity space in the tree bole can promote a positive feedback where a subsequent wildfire has an enlarged area of dry wood matter and accumulated fine fuels to ignite (Figure 61-62). The presence of charring on buttress hollows suggests rainforest trees in the study area have been repeatedly burned and the callous or wound wood has not been allowed to close because of repeated scarring. On the larger trees, the cavities can form voids following repeated fires, which create large spaces between the tree bole and buttress roots permitting fires to ignite directly under the bole (Figure 62, 70). Over time, these voids weaken the structural integrity of the tree and can lead to tree breakage and collapse (Figure 71).

Multi-stemmed trees are a characteristic feature of larger and older *N. moorei* specimens, where multiple cohorts of stems arise from a single swollen stem base promoting episodic recruitment of new stems following disturbance (Johnston and Lacey 1983). Basal hollows associated with superficial wounds resulting from low-intensity fires have been described elsewhere in rainforests (Putz 2013) and may lead to positive feedback mechanisms where repeated low-intensity fire events lead to increased hollow formation which, due to their high proportion of dry wood tissue and accumulated litter, are more susceptible to further ignition.

Charring and callous formations primarily occurred on the windward side of the larger trees. From a theoretical perspective (Dickinson and Johnson 2001, Michaletz and Johnson 2007) this suggests that the predominant fire behaviour experienced by the larger rainforest trees is low-velocity litter fires that progress slowly through the rainforest under conditions of low intensity and flame height.

If this is correct, it is consistent with fire managers' observations across multiple fires in northern NSW that surface or litter fires will burn beneath rainforest stands at low intensity and rates of spread and will transgress topographic and fuel moisture gradients during extended spring droughts.

FIGURE 60: VETERAN *NOTHOFAGUS MOOREI* TREE COLLAPSES FOLLOWING WILDFIRE DAMAGE ON NOVEMBER 7 2019 AND PHOTOGRAPHED IN MAY 2020. THE DOMINANT STEM ON THE TREE HAS COLLAPSED AND RESPROUTING IS OCCURRING FROM BASAL MERISTEMATIC TISSUE ASSOCIATED WITH COPPICE STEMS ON THE SAME PLANT. THE LARGE COPPICE STEMS ARE THOUGHT TO HAVE ORIGINATED FROM A WILDFIRE IN 1956. (IMAGE: ROSS PEACOCK).

## PRE-EXISTING DAMAGE

Pre-existing stem damage and defects were frequently observed in the rainforest trees of the study area. Damage took a range of forms within canopy, branch, stem, and basal portions of the tree. In the latter, heartwood decay due to the action of saprophytic organisms often created hollows extending vertically through the bole along the main vertical axis of wood cells thus avoiding the chemical defences of living sapwood on stem peripheries. Hollows and other internal defects are pronounced on larger and irregularly shaped rainforest trees and can account for up to a 30% loss of individual tree biomass (Nogueira et al. 2006). Internal or hidden defects are pronounced in *Nothofagus*. In Tasmania, they are highest on infertile and poorly drained sites and are often difficult to predict from external features of the tree (Hickey and Felton 1987).

Pre-existing stem damage, as a mortality risk factor, was assessed for each tree by observing the area of the lower trunk with nil, low, moderate, or high proportions of hollows and cavities. Pre-existing stem damage was significantly related to post-fire tree mortality across all tree species (Figure 63 Pearson Chi-sq = 58.62, df = 3, $p < 0.001$), including *Nothofagus moorei* (Figure 64 Pearson Chi-sq = 37.31, df = 3, $p < 0.001$)

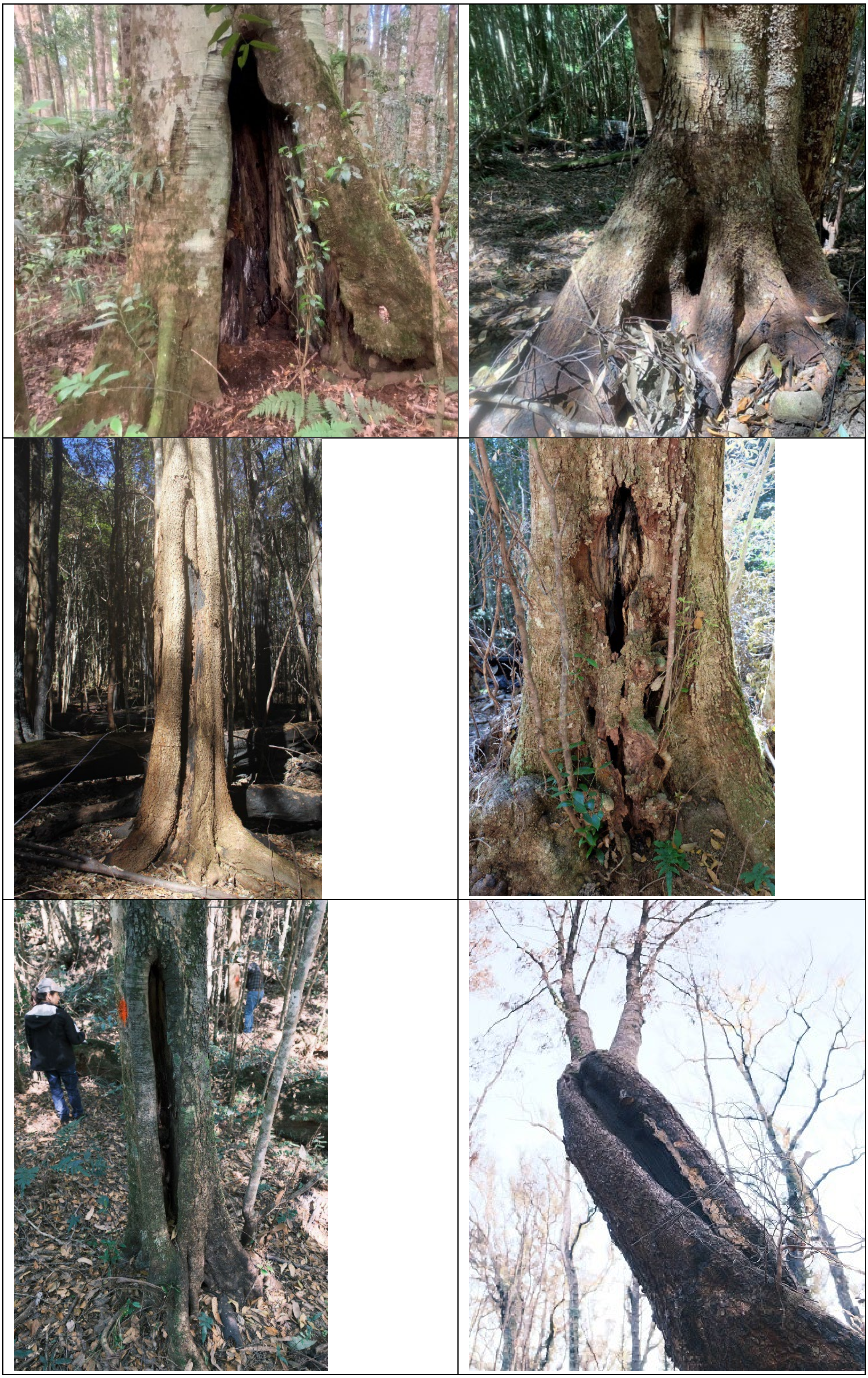


FIGURE 61: EXAMPLES OF THE TYPES OF CAVITIES AND HOLLOWS WHICH NATURALLY FORM IN RAINFOREST TREES (*CERATOPETALUM APETALUM*) WITH AGE. THESE CAVITIES ACCUMULATE DRY WOOD AND LEAF MATERIAL AND IGNITE DURING EMBER ATTACK (IMAGES ROSS PEACOCK).

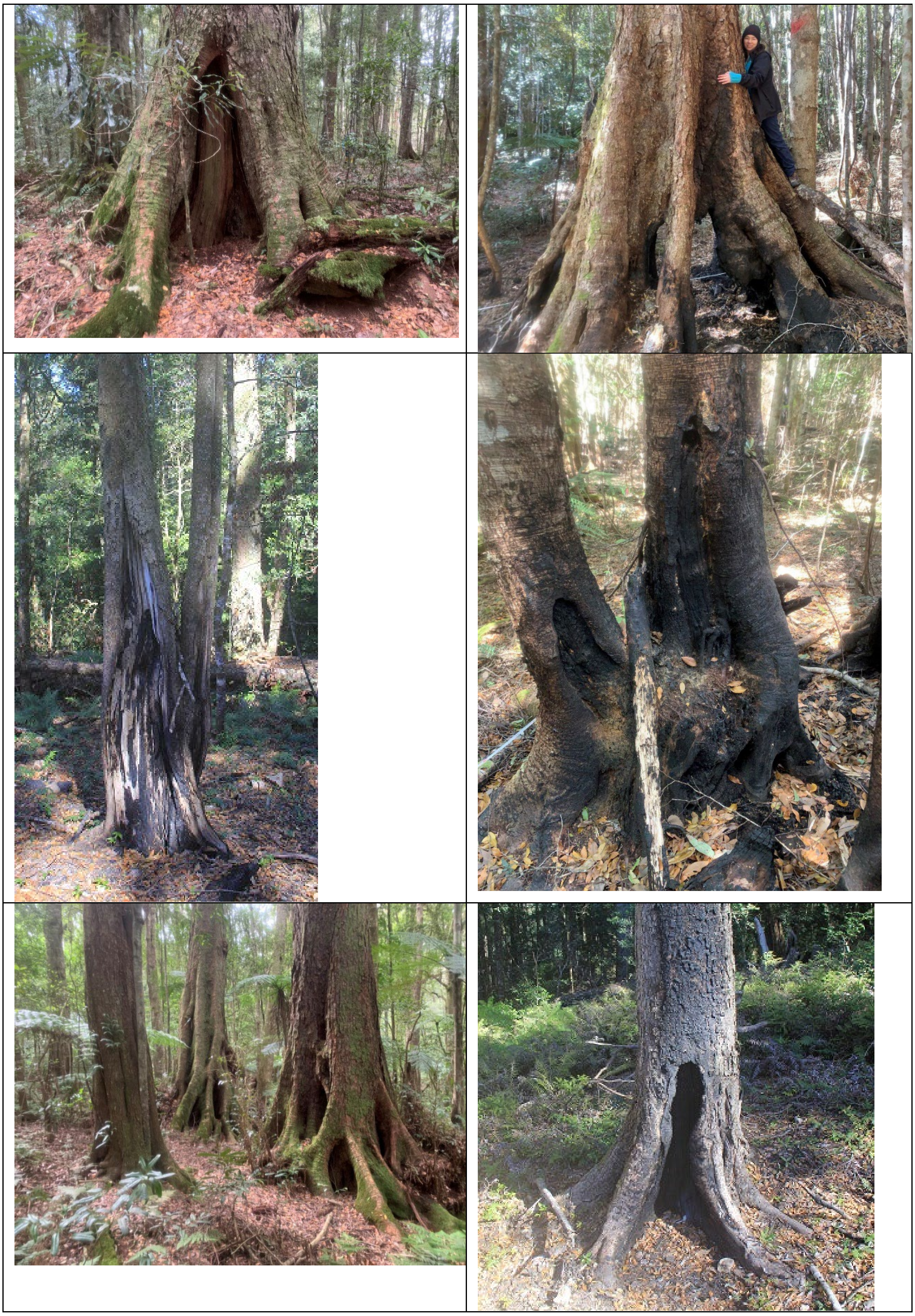


FIGURE 62: EXAMPLES OF THE TYPES OF CAVITIES AND HOLLOWS WHICH NATURALLY FORM IN RAINFOREST TREES (*NOTHOFAGUS MOOREI*) WITH AGE. THESE CAVITIES ACCUMULATE DRY WOOD AND LEAF MATERIAL AND IGNITE DURING EMBER ATTACK. (IMAGES ROSS PEACOCK).

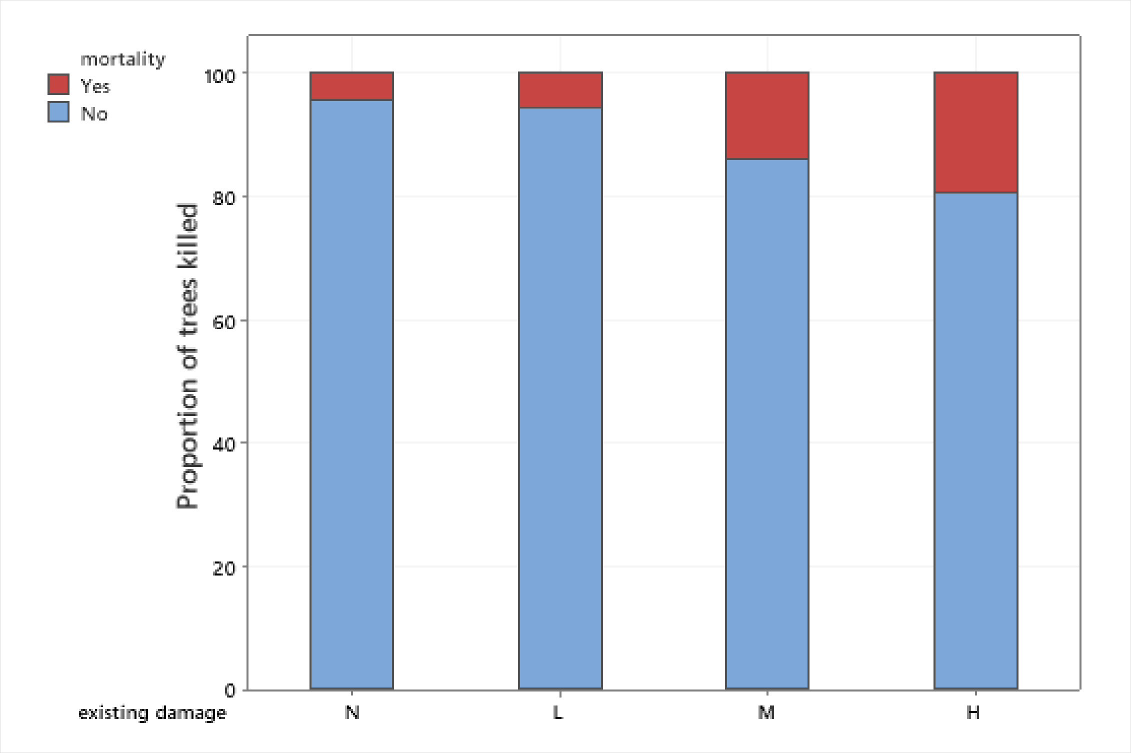


FIGURE 63: RELATIONSHIP BETWEEN EXISTING TREE DAMAGE (NIL, LOW, MODERATE, HIGH) ACROSS ALL TREE SPECIES AND POST-FIRE MORTALITY

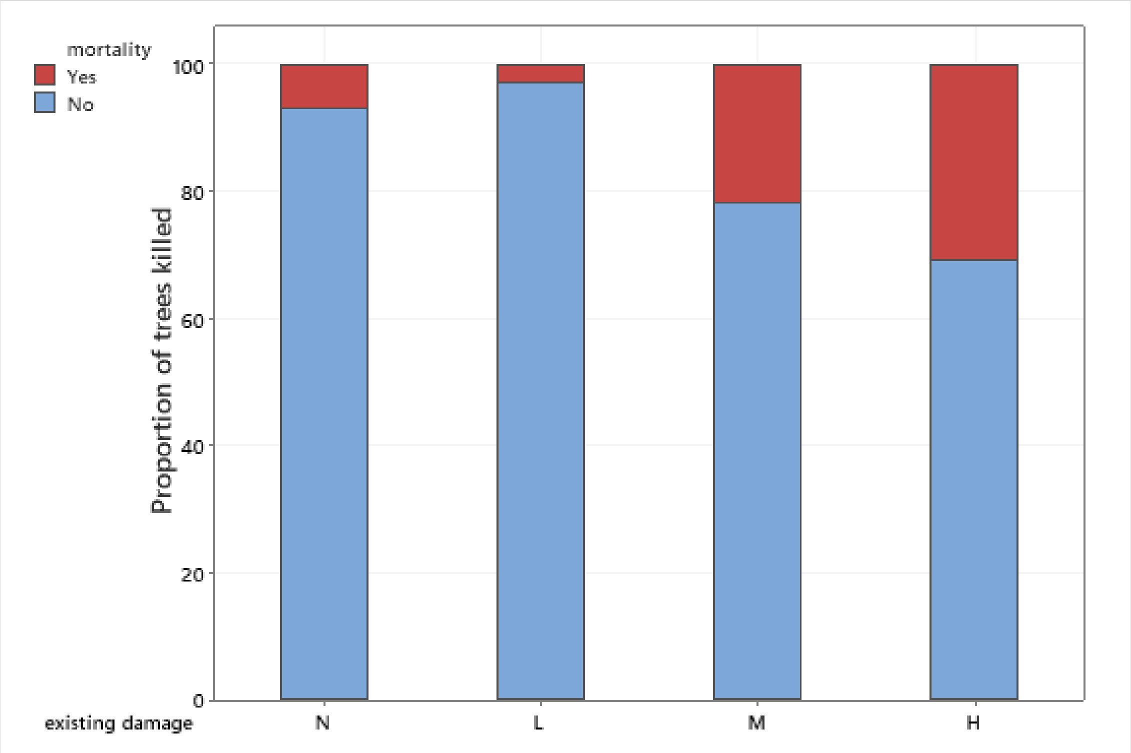


FIGURE 64: RELATIONSHIP BETWEEN EXISTING TREE DAMAGE (NIL, LOW, MODERATE, HIGH) IN NOTHOFAGUS MOOREI AND POST-FIRE MORTALITY.

## TREE HEIGHT

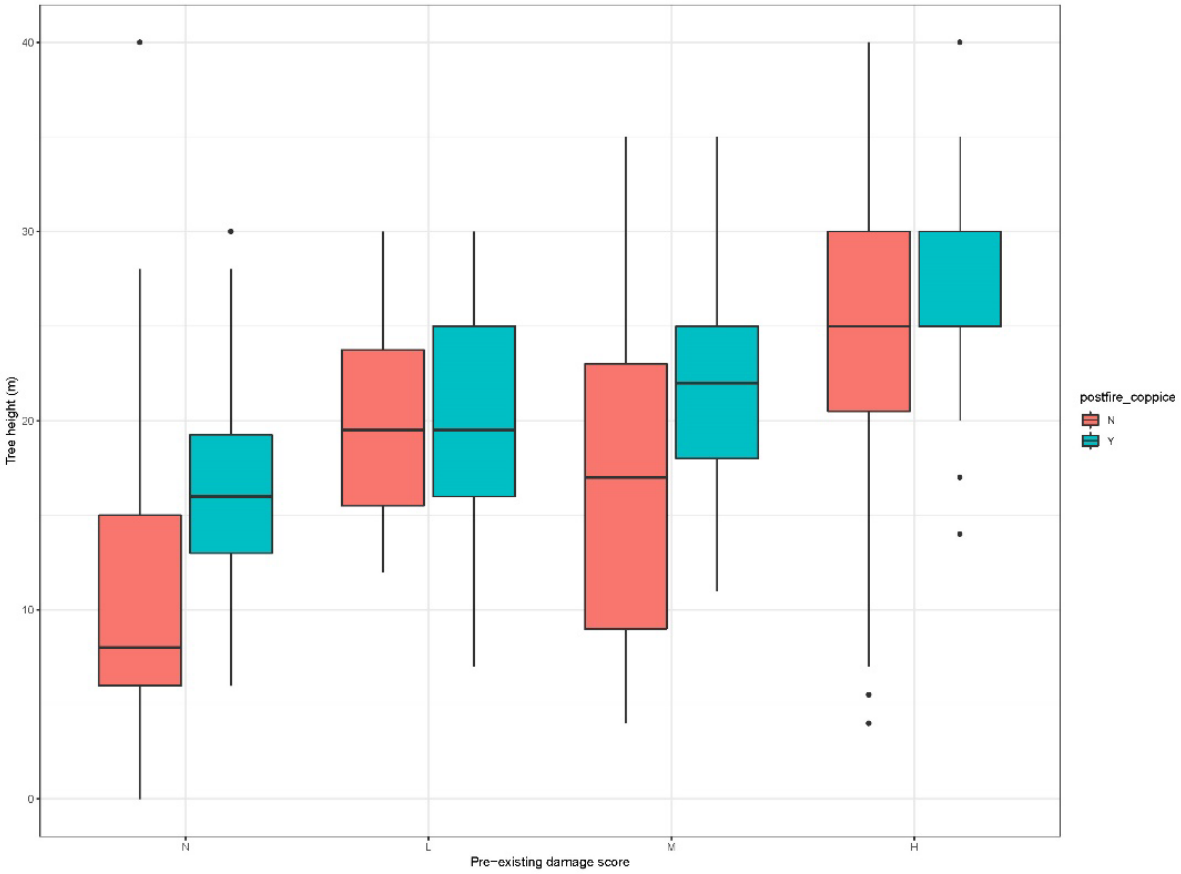
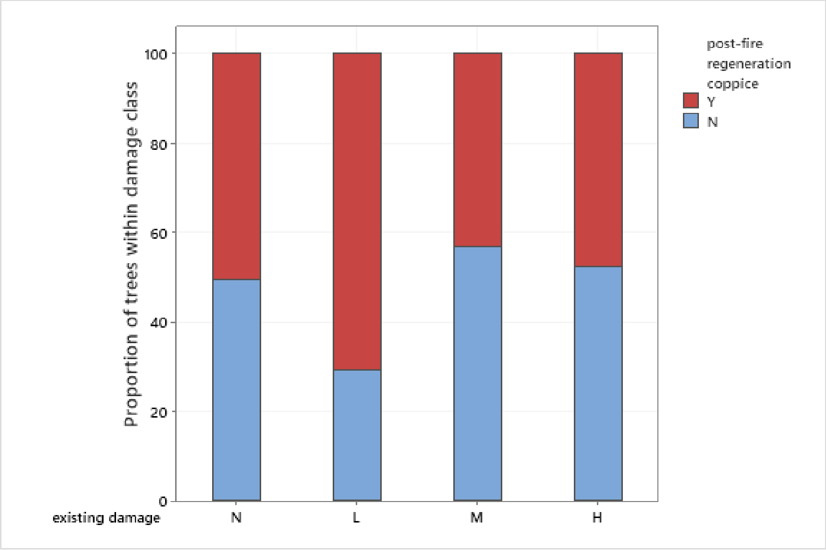


FIGURE 65: RELATIONSHIP BETWEEN EXISTING TREE DAMAGE, TREE HEIGHT AND POST-FIRE COPPICE RESPONSE FOR ALL TREE SPECIES

The post-fire coppice response of rainforest trees across species varied both with extent of pre-existing damage and tree height (Figure 65). Taller trees were more likely to be in the highest category of pre-existing damage. This may be an age effect in which older and taller trees have been subjected to repeated fire-inducing wounds and hollows. However, the post-fire coppice response did not differ in this category, although it did for trees with only moderate pre-existing damage or no damage (Figure 65, one-way ANOVA F(3, 694) = 16.35, p<0.001).



Post-fire coppicing was most frequently observed when only low levels of pre-existing damage were present (Figure 66).

FIGURE 66: RELATIONSHIP BETWEEN PRE-EXISTING DAMAGE AND POST-FIRE COPPICE RESPONSE FOR NOTHOFAGUS MOOREI

Within the pre-existing damage classes, the mean height of trees exhibiting a coppice response was greater than those not exhibiting a coppice response although there is considerable overlap. When pooled across all pre-existing damage classes, trees that coppiced tended to be larger (median height = 18m) than those that did not coppice (median height =10m).

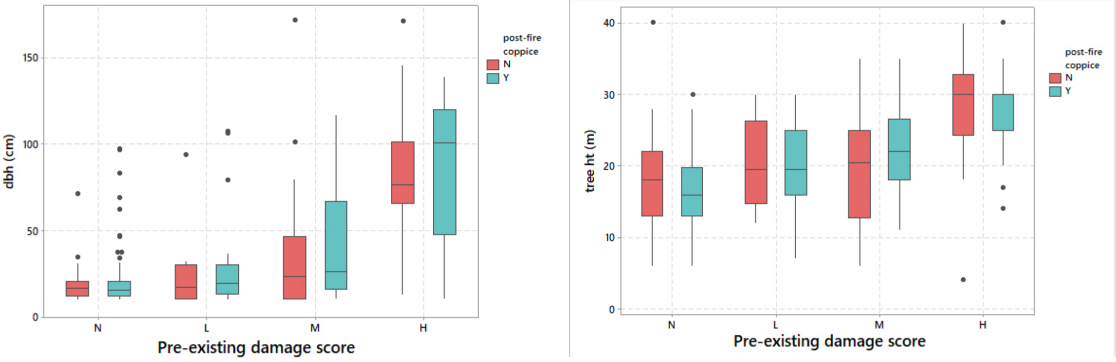


FIGURE 67: RELATIONSHIP BETWEEN PRE-EXISTING TREE DAMAGE, TREE DIAMETER (LEFT), TREE HEIGHT (RIGHT)AND POST-FIRE COPPICE RESPONSE IN *NOTHOFAGUS MOOREI*. THE SAMPLE IS RESTRICTED TO STANDS WHICH BURNT.

Pre-existing damage in *Nothofagus* was more strongly associated with dbh than tree height (Figure 67). Larger DBH trees were more likely to exhibit buttress hollows from repeated fire impacts. Whether a tree has coppiced or not is very marginally related to DBH (p = 0.049) with coppicing associated with slightly larger trees. Also, post-fire coppicing of *Nothofagus* was strongly associated with the level of pre-existing damage (Figure 67, one-way ANOVA F(3, 316) = 79.06, p<0.001).

*Nothofagus* trees with a greater amount of pre-existing damage were generally taller than trees with no or low damage, a likely age effect. For trees with no damage or medium damage, the taller trees were more likely to coppice, but there is considerable overlap. When pooled across all pre-existing damage classes, trees that coppiced were marginally shorter (median height = 17.1m) than those that did not coppice (median height = 18.8m, one-way ANOVA F(1, 694) = 8.50, p=0.004). There was also some indication (graphically) that stands with shorter maximum heights (i.e., height of the tallest tree) experienced less mortality as a percentage of stand basal area killed. Again, there was considerable spread in mortality values at the taller heights. It is clear however that char height, as a measure of flame height and fire line intensity, was related to the health of trees post-fire (Figure 68, one-way ANOVA F(3, 694) = 245.79, p<0.001).

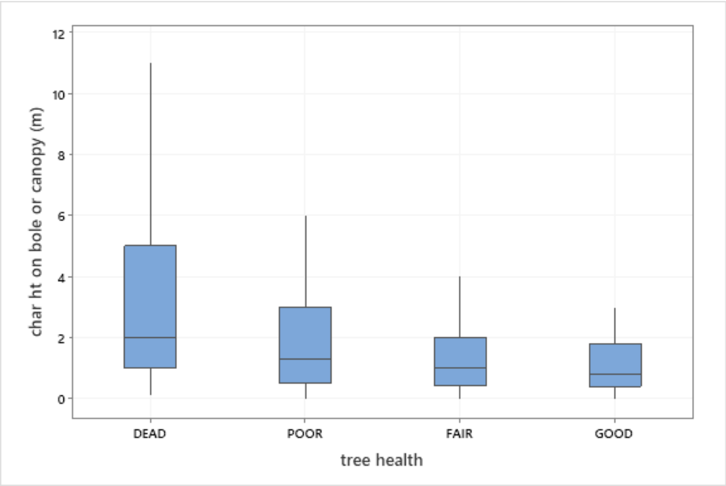


FIGURE 68: RELATIONSHIP BETWEEN CHAR HEIGHT ON BURNT TREES AND TREE POST-FIRE HEALTH.

For *Ceratopetalum* the patterns of post-fire coppicing however are much more muted. Larger trees are associated with greater pre-fire damage and for those that are damaged, it is the larger trees that are most likely to coppice.

2013

2020

FIGURE 69: VETERAN *NOTHOFAGUS MOOREI* TREE SPOKES TRAIL WERRIKIMBE NP EXHIBITING EFFECTS OF REPEATED FIRES. THE TREE WAS PHOTOGRAPHED AFTER THE 2013 (LEFT) AND 2019 (RIGHT) FIRES. IT WAS ASSUMED TO HAVE ALSO BEEN BURNT IN 1965/66 AND 1994. *NOTHOFAGUS MOOREI* CAN TOLERATE REPEATED FIRES UNTIL THEIR BUTTRESSES COLLAPSE OR THEIR ROOT SYSTEMS LOSE SOIL BINDING STRENGTH. (IMAGE: ROSS PEACOCK)

FIGURE 70: VETERAN *NOTHOFAGUS MOOREI* TREE IGNITES FROM CAVITIES IN BUTTRESS HOLLOWS DURING AN EXPERIMENTAL FIRE IN WERRIKIMBE NP 2013. THIS TREE COLLAPSED THE FOLLOWING DAY. (IMAGE: ROSS PEACOCK)

2012 (BURNT IN 1965/66 AND 1994)

FOLLOWING BURNING IN 2013

2015

2017

2020

FIGURE 71: TIME SERIES OF A VETERAN *NOTHOFAGUS MOOREI* TREE WERRIKIMBE NP 2012-2020. THE TREE HAS BURNT FOUR TIMES IN THE LAST 50 YEARS BEFORE IT COLLAPSED FOLLOWING THE 2019 WILDFIRE. (IMAGE: ROSS PEACOCK)

## TREE MORTALITY PATTERNS

Rainforest tree mortality post-fire occurred subsequent to multiple fire events gradually enlarging the buttress cavity (Figure 72), from trees snapping above the buttress, from canopy attrition or secondary effects when the largest dominants collapse and snap smaller trees. Mortality was observed to be almost immediate during the 2019/20 wildfire season in northern NSW (within a day of the fire path), however it could be delayed for years as trees progressively weaken structurally or loss of hydraulic conductivity impairs canopy condition.

FIGURE 72: DAMAGE AND COLLAPSE OF VETERAN *NOTHOFAGUS MOOREI* TREES AT WERRIKIMBE NP FOLLOWING THE 2019 WILDFIRE. THE TREE ON THE LEFT SURVIVED DESPITE A SIGNIFICANT CAVITY. (IMAGE: ROSS PEACOCK)

The mean annualized rates of tree mortality in unburnt rainforest stands for stems > 10 cm DBH was 0.75% (95% CI 0.529-0.917, N=194, Figure 4-5). This is based on averaging across thousands of measured and tagged trees at multiple locations within temperate rainforest. However, when mortality is estimated as a probability function across all trees in the 15 stands measured in this study, the probability of a tree being dead in the unburnt stands is between 1 and 5%, increasing gradually with tree diameter (Figure 73) independently of stand density (Figure 74).

Tree mortality patterns were examined in relation to tree height, stem diameter and dominance class as surrogates for tree size and age. The focus of the analysis is *Nothofagus* because it is the canopy dominant and the species that contributes the majority of the stand basal area.

The probability of *Nothofagus* tree mortality following wildfire increases with tree diameter (Figure 75-76). Larger and older trees have buttress cavities more likely to ignite and weaken the tree (Figure 72). There was a weak trend of shorter trees experiencing less mortality as a percentage of total stand basal area killed; however, there was considerable spread in mortality values at the taller tree heights (Figure 77). There is no significant difference (one-way ANOVA p= 0.305) in the proportion of basal area killed amongst the different plot-scale fire severity classes (Figure 77). This suggests that the remotely sensed fire severity classes do not adequately represent trends at the individual tree scale between mortality and fire severity. The same trend is evident when examining the proportion of tree basal area killed (one-way ANOVA p= 0.244). Remotely sensed fire severity is a metric based on canopy reflectance, and does not aim to assess fire severity at the scale of the individual tree.

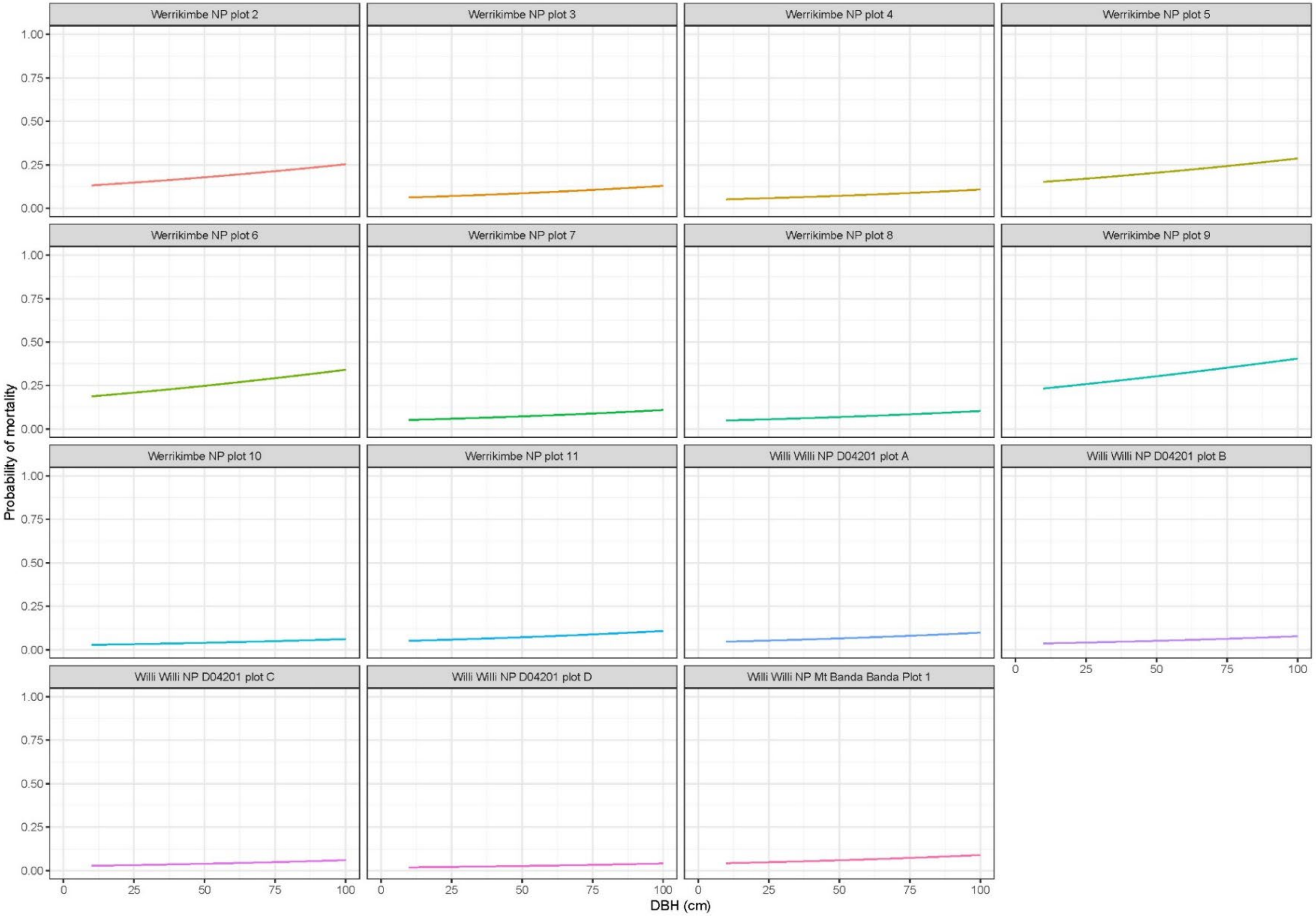


FIGURE 73: THE PROBABILITY OF TREE MORTALITY FOLLOWING WILDFIRE DAMAGE ACROSS ALL SAMPLED STANDS

THE FOUR PANELS LABELLED (D04201) REPRESENT UNBURNT STANDS AND THE REFERENCE STATE FOR TREE MORTALITY.

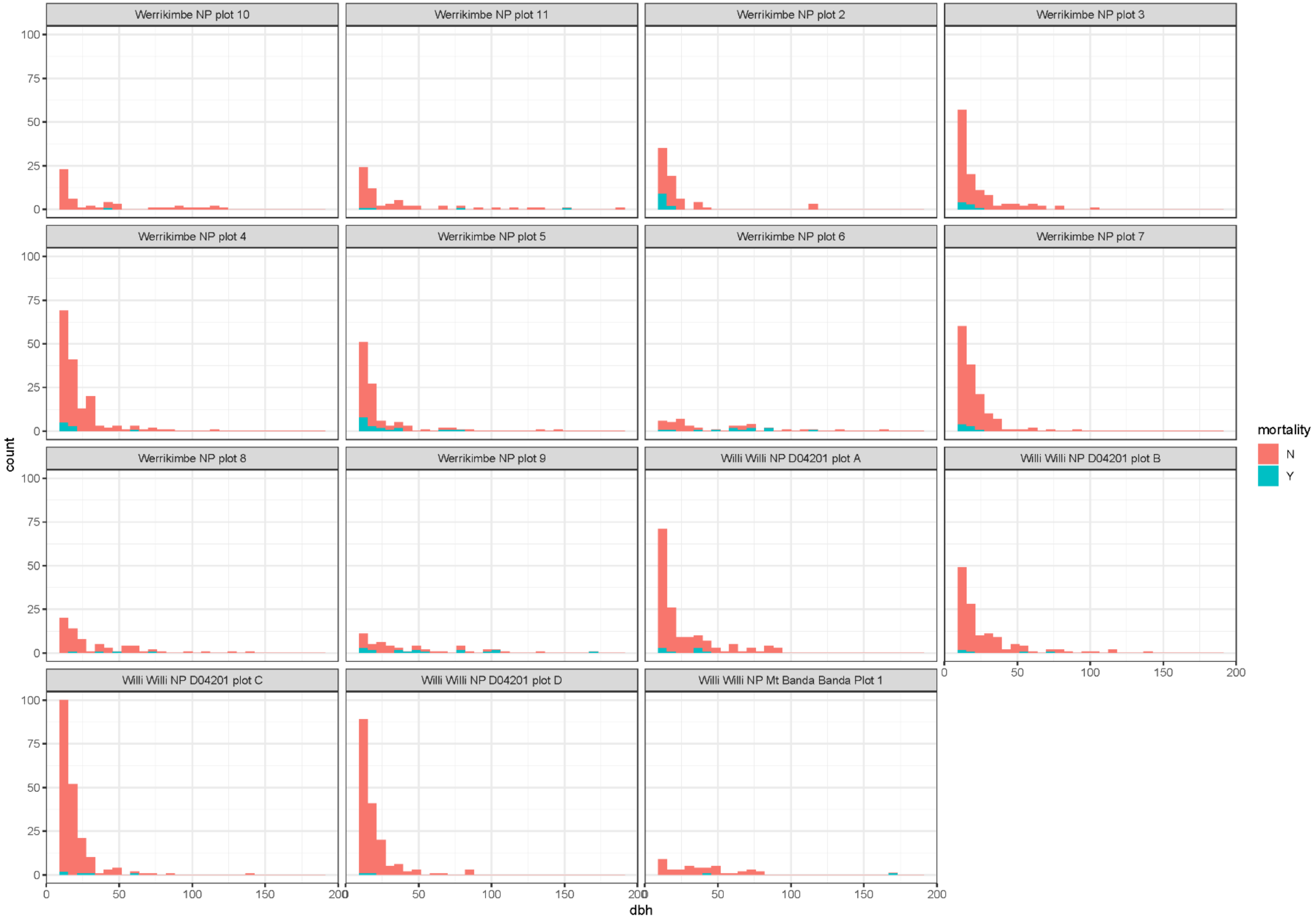


FIGURE 74: THE PROPORTION OF INDIVIDUAL TREES OF *NOTHOFAGUS MOOREI* IN THE TOTAL POPULATION SAMPLES WHICH ARE KILLED BY WILDFIRE ACROSS ALL SAMPLED STANDS

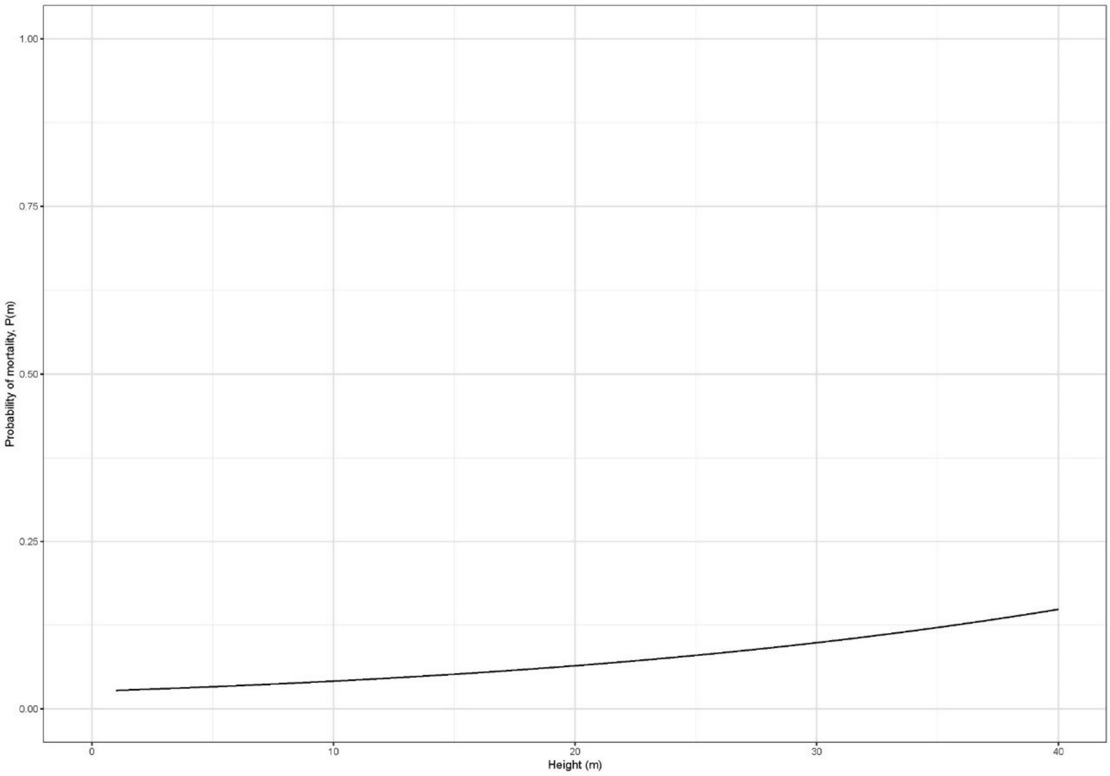


FIGURE 75: THE PROBABILITY OF *NOTHOFAGUS MOOREI* TREE MORTALITY FOLLOWING WILDFIRE DAMAGE AS A FUNCTION OF TREE HEIGHT.

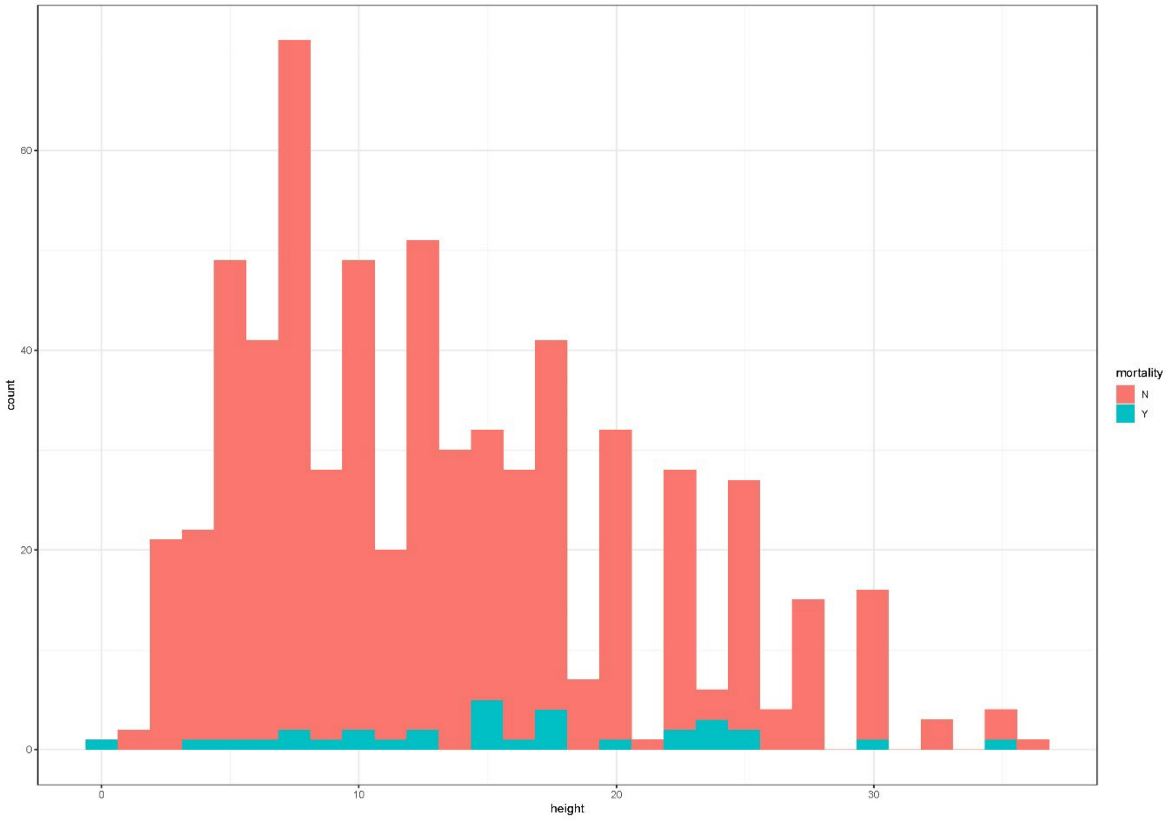


FIGURE 76: THE PROPORTION OF INDIVIDUAL TREES OF *NOTHOFAGUS MOOREI* IN THE TOTAL POPULATION SAMPLES WHICH WERE KILLED BY WILDFIRE

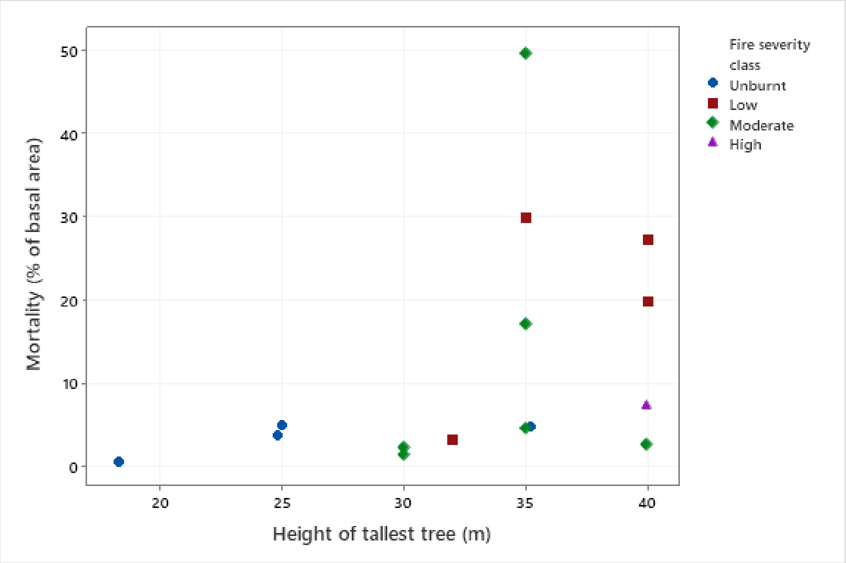


FIGURE 77: THE PROPORTIONAL BASAL AREA OF TREES DYING FOLLOWING WILDFIRE DAMAGE EXPRESSED AS THE HEIGHT OF TALLEST TREES IN EACH SAMPLE PLOT.

The mean diameter of *Nothofagus* differed significantly between surviving and non-surviving trees within dominance classes (Figure 78, one-way ANOVA F(1, 316) = 19.45, p<0.001) in each dominance class the mean diameter of dead trees was larger. For *Nothofagus*, while there is low mortality (~10%) for trees <40 cm DBH and higher mortality (15-25%) for trees >40 cm DBH, the statistical model is not significant (Figure 75).

Although *Nothofagus* mean tree height was greater within dominance classes for dead trees, the difference was not significant (Figure 78). There does appear to be a strongly significant effect of height, although, counterintuitively, it suggests that taller trees have a higher probability of mortality (1 m tall tree has 5% probability of mortality, for 40 m tall tree it is 30%). The overall relationship between individual trees and mortality requires further assessment. While there was a slightly positive relationship between size and probability of mortality, this may be a result of sampling issues (fewer large trees, so the influence of one dead tree in a large size class is much greater than one dead tree in a smaller size class). There were some obvious differences in this relationship between plots (Figure 77).

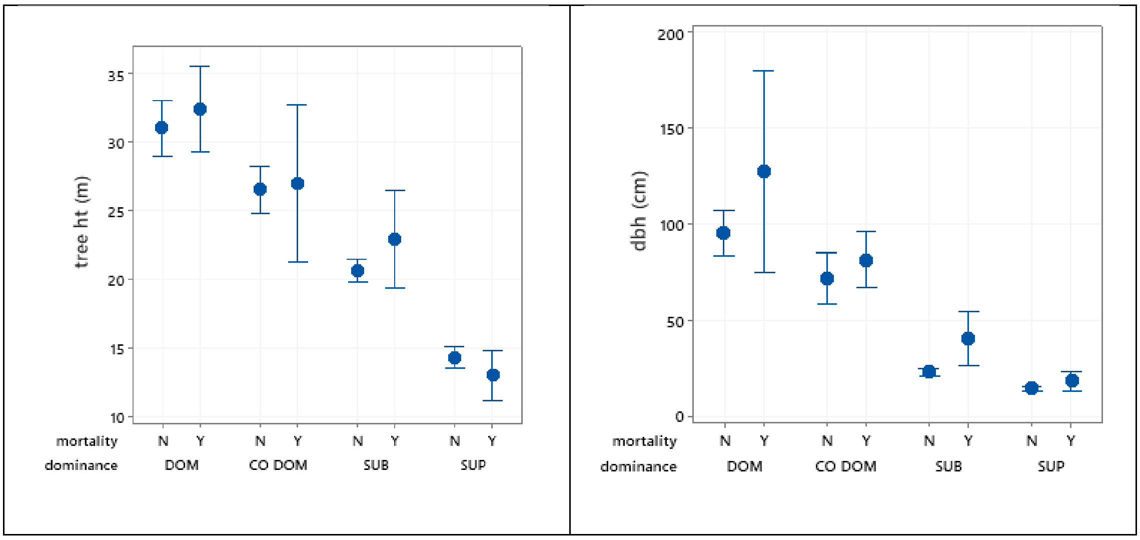


FIGURE 78: RELATIONSHIP BETWEEN TREE DOMINANCE CLASS (DOMINANT. CO-DOMINANT, SUB-DOMINANT AND SUPPRESSED), POST-FIRE MORTALITY AND TREE SIZE.

# SUMMARY

NSW has between 549,000 and 788,999 ha of rainforest across nine formation types (Figure 79). Of these 112,145 ha are reserved in the Gondwana Rainforest World Heritage properties. Across NSW, 18.1% of the rainforest burnt during the 2019/20 wildfire season. Within the Gondwana Rainforests, 8.6% of the rainforest burnt. In the Gondwana Rainforests the greatest impacts of fire in rainforest were in the Dry Rainforest and Northern Warm Temperate Rainforest types, particularly sections within Werrikimbe and Oxley-Wild Rivers NP. The rainforests of northern NSW are being impacted by wildfire at a scale unanticipated in earlier planning.

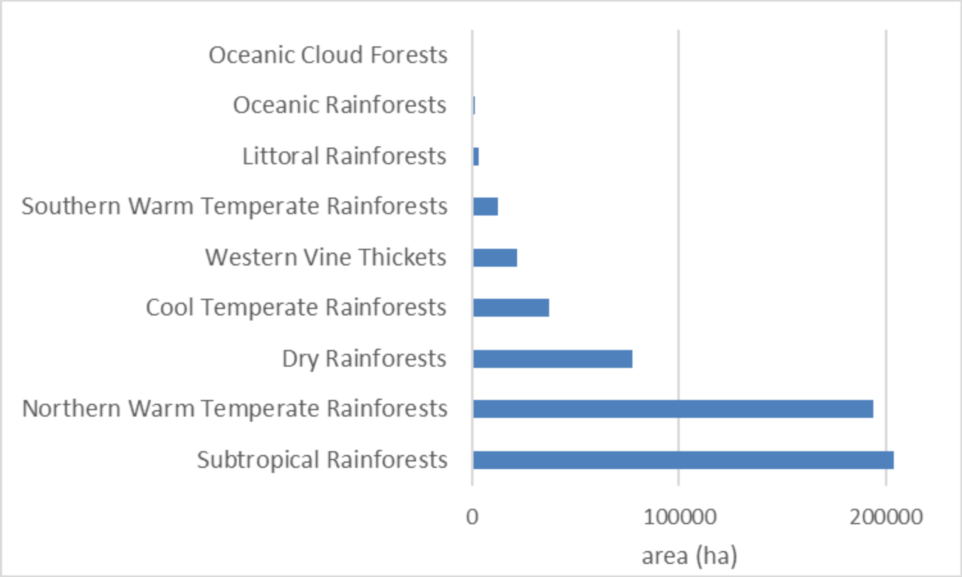


FIGURE 79: THE PROPORTIONAL AREA OF EACH RAINFOREST FORMATION IN NSW.

The focus of this study was the cool temperate rainforests where the majority (70.5%) of stands in New South Wales are <10 ha in size (Figure 80). State-wide, 11.2% of cool temperate rainforests burnt during the 2019/20 wildfire season. Proportionally, smaller stands will have a greater perimeter area exposed to wildfire impacts, and potentially ongoing attrition and mortality of edges.

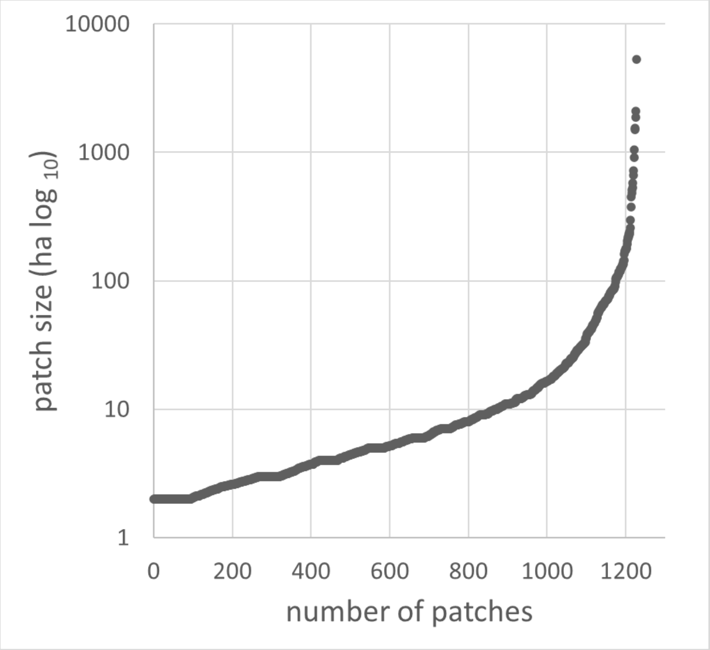


FIGURE 80: THE FREQUENCY OF COOL TEMPERATE RAINFOREST PATCH SIZES IN NSW.

The temperate rainforests of the Gondwana Rainforests are notable for their distinctive floristic assemblages, high level of endemism, high stand basal areas, slow tree growth, and episodic seedling recruitment. Many stands exhibit evidence of canopy dieback, possibly an endemic condition exacerbated by previous harvesting disturbances (Figure 81). Based on an analysis of similar stands near Dorrigo, rainforests are predicted to take a century to recover to their pre-harvest structure and composition following harvesting. Trees in these stands may be more susceptible to ignition and collapse, assuming they have a higher proportion of trees with stem cavities present.

FIGURE 81: RAINFOREST HARVESTING AT MT BOSS STATE FOREST, 1980. SOURCE: FLOYD 1990 FIGURE 42

With widespread fire damage across the extent of NSW’s temperate rainforests, the current study used an existing long-term research plot network in an area where detailed fire severity mapping and other fire intelligence was able to inform a stratified sampling design. The intent of the study design was to inform post-fire recovery planning by assessing the significance of the impacts of the 2019/20 wildfire season on rainforest stand structure, composition, tree mortality and regeneration strategies. The existing long-term plot network provided a baseline to assess the significance of the 2019/20 wildfire season by applying the long-term plot trends in microclimate variability across vegetation boundaries, inter-annual fuel biomass, and landscape fire behaviour from the 1950s. This long-term context and the sampling across a gradient of 2019/20 fire intensity informed post-fire recovery workshops convened by the Commonwealth and NSW governments in 2020/21 and expert workshops supporting the Multi-Criteria Analysis Shell for Spatial Decision Support tool. This approach also provided opportunities to inform the current and newly emerging settings for bush fire risk planning in NSW for environmental assets including the Gondwana Rainforest components of the NSW reserve system.

The majority of the impacts of wildfires during the 2019/20 season in rainforests occurred over a small number of days when a combination of the extended spring drought, multiple ignition sources and synoptic conditions led to extreme and catastrophic fire conditions. With sufficient biomass being available, the four hypothetic ‘switches’ of Bradstock (2010) were activated and fire behaviour was effectively unconstrained. While a high-intensity wildfire will burn temperate rainforest from a fire front or flank (especially when driven by a north or westerly wind), the predominant behaviour observed from field evidence suggests most northern NSW rainforests in the 2019/20 season were instead subject to ember attack and did not sustain a fire beyond a short run. Fire runs were extended during uphill runs facing the prevailing winds or where the rainforest canopy and understorey was more open on exposed and rocky landforms. A good example of this is the extent of fire impacts within the small, exposed stand of 39 individual trees of *Nothofagus moorei* at Cathedral Rock National Park (Colin Bale, pers. comm). The stand was impacted by a moderate to high severity fire, which also consumed much of the shallow soil organic matter.

Evidence from repeated fires in the Hastings-Macleay area since the 1950s suggests the front and flank fires are the problem for rainforest patch persistence, not the spotting fires. While spotting fires led to fire impacts being dispersed over a larger area, spotting ignitions were characterized by very short fires runs of less than 100m$^2$ or, at times, only single tree ignitions. This behaviour is likely due to the lack of fuel continuity in rainforests. Where transitional communities occurred and rainforest existed as an understorey below a forest dominated by *Eucalyptus* spp. (or *Lophostemon confertus*), more extended fire runs occurred due to the nature of the non-rainforest ground fuels. It is noteworthy that much of the eucalypt forests and woodlands providing the landscape matrix for temperate rainforest in the Hastings-Macleay area of the Gondwana Rainforests also burnt in 1994 and 2013. This suggests that in 2019 fuel loads across the broader landscape were not necessarily high or at their equilibrium mass. This is a key consideration for any exploration of options for reconfigured fuel management objectives within the reserve system. Traditional approaches to managing assets by developing Strategic Fire Advantage Zones, where fuel mass is managed differently from the broader Land Management Zones, may not necessarily preclude wildfire damage to rainforest patches unless the level of treatment imposed is significant (King et al. 2008). Similarly, fuel management surrounding rainforest patches is not an effective strategy to address spotting or ember attack within rainforest patches. The low equilibrium fine fuel biomass and thick bark of rainforest tree species make hazard-reduction burning within rainforest patches unfeasible as a risk management strategy.

The recurring pattern of fire behaviour in the study area indicates that under severe weather conditions the influence of landscape factors and fuel management will be reduced and temperate rainforest patches will only be partially protected within their topographic refuges. Typically, this results in rainforest stand edges being subject to repeated attrition. For rainforest species with slow growth rates and limited seedling regeneration, edges are expected to contract through tree damage, attrition, and collapse. Rainforest edges subject to repeated wildfire impacts were colonized by pioneer species (e.g. *Callicoma serratifolia*), not rainforest species. While rainforest edges are naturally dynamic and at times diffuse, edges in cool temperate rainforest were well defined by large, old canopy dominant trees and a lack of tree sapling regeneration.

An analysis of historical fire management records dating back 70 years has indicated that the peak month for wildfires in northeastern NSW has advanced by one to two months and, consequently, is approaching the driest months of the year. The convergence of drier springs, increased lightning ignitions on dry fuel beds and remote ignitions is a challenging prospect for wildfire suppression.

An analysis of long-term fine fuel inputs has provided some unique insights into the distinct seasonal and inter-annual patterns related to rainfall and temperature. Fine fuel inputs increase in wet years and seasonally in spring when soil moisture reaches its minimum. Instantaneous sampling of litter fuel moisture across *Eucalyptus* forest and adjacent rainforest boundaries identified that fuel moisture differed significantly across the boundary. However, when soil volumetric moisture content approaches 10-20%, usually following a period of drying extending over several months, this moisture differential is lost. Over a period of a decade of monitoring soil moisture, each time soil moisture content approached this critical minimum threshold, a wildfire burnt into rainforest in the Hastings-Macleay area or neighbouring reserves.

The 2019/20 wildfire season was the first in NSW for which fire severity and extent mapping were made available rapidly across the landscape to inform impact assessments and recovery planning. We used this mapping to stratify the plot-based forest sampling across the landscape. At a landscape scale, the remotely sensed fire severity classification performed well at predicting the relative proportion of trees exhibiting different fire severity responses at the forest stand level, despite the challenges of detecting understorey fires in rainforest by remote sensing where the impacts on canopy tree health can be delayed or obscured by the multiple tree strata. The remotely sensed fire severity classes in themselves are not a good predictor of the proportion of tree biomass killed by the fire; there may be other factors at the individual tree level that are more relevant. Predicting fire severity for low-intensity understorey fires in rainforest using canopy reflectance measures is a challenging task. However, this study provided data that was used to improve the fire severity classification model.

Wildfires impacting temperate rainforests in northern NSW will alter forest composition, structure, and function for not only the canopy trees but the larger number of non-vascular species that rely on this habitat as a substrate. The largest proportional change will be in the common canopy dominants, especially those on the advancing or retreating rainforest margins where attrition is most rapid. Prospects for structural recovery are inevitably limited in the short term due to the slow recruitment and growth of replacement trees and potentially delayed canopy dieback associated with increased exposure and windthrow.

Post-fire regeneration strategies for northern NSW temperate rainforest tree species predominantly rely on basal resprouting, with a smaller contribution from stem sprouting. Relevant studies documenting resprouting behaviours in temperate rainforests are uncommon and this lack of information limits the development of relatively simple models of resilience and persistence in the temperate rainforests of northern NSW. In the study area, data on a range of regenerative traits were collected to address this knowledge gap and assist with interpreting patterns of tree fire damage, regeneration, and mortality. Post-fire regeneration was heavily weighted towards vegetative mechanisms (i.e. sprouting) for *Nothofagus* and *Ceratopetalum*. Seedling regeneration for the rainforest canopy dominants was infrequent, seedling density declined rapidly post-fire. *Nothofagus* is relatively light demanding at the seedling and sapling stage, while *Ceratopetalum* is more shade tolerant. The implication is canopy attrition and opening due to loss of condition post-fire may favour *Nothofagus* seedling regeneration post-fire.

The post-fire coppice response of rainforest trees varied amongst species both with extent of pre-existing damage and tree height. Post-fire coppicing was most frequently observed when only low levels of pre-existing damage were present on the tree stem.

In terms fire damage, charring and callous formations were predominantly on the windward side of the trees, particularly the larger trees. This suggests that most of the larger rainforest trees experienced slow-moving, low-intensity fires. Land managers who had managed fires corroborated these findings and frequently referred to rainforest fires in the study area as litter fires. The evidence of litter fires was ubiquitous throughout all of the rainforest stands surveyed. All stands exhibited evidence of multiple low-intensity fires in the past.

Across all tree species, the majority of individual tree stems that showed evidence of direct fire impacts (e.g. stem charring) were also coppicing (either at the base, along the stem, or in the canopy). Trees that coppiced post-fire tended to be taller than those that did not. There was also some indication that shorter stands (i.e., average height of the tallest trees was lower) experienced less mortality as a percentage of stand basal area killed.

At the stand level, temperate rainforests with more tree biomass, particularly of larger trees, tended to capture more embers and provide a dry fuel source for ignition. This suggests that stands with a greater proportion of trees in the larger size classes stages may be more susceptible to ignition.

Pre-existing stem damage in the form of buttress hollows, scars and callous formations was significantly related to post-fire tree mortality across all tree species. Larger, older trees had higher levels of pre-existing stem damage, and were more likely to die and collapse following burning. The probability of *Nothofagus* tree mortality following wildfire was also observed to increase with tree diameter. This is potentially an age effect where older and larger (diameter and height) trees have been subject to fire-inducing wounds and hollows in the past. Counterintuitively, taller trees had a higher probability of mortality, in most studies of post-fire tree mortality, it is the smaller trees with a higher probability of mortality.

The loss of these larger, older canopy dominant rainforest trees has a range of implications for forest composition, structure and function, not only for the maintenance of the canopy and microclimate, but the larger number of non-vascular epiphytic species that rely on this habitat as a substrate. Monitoring individual canopy trees since 2007 indicates the greatest impacts of the fires will be on the trees occupying the advancing or retreating rainforest margins. Prospects for structural recovery are inevitably limited in the short term due to the slow recruitment and growth of replacement trees and the potential for canopy dieback associated with increased exposure and windthrow.

Tree mortality often lagged behind the fire itself. Repeated fires were observed to gradually enlarge tree buttress cavities resulting in trees snapping above the buttress and gradual canopy attrition from hydraulic failure. In the 2019/20 wildfires, mortality was either immediate (within a day of the fire path) or delayed one to two years as trees progressively weakened and eventually collapsed.

Historic mapping, archival management records, and newspaper reporting provide evidence for rainforests burning in northern NSW since at least 1915. The recurring pattern leading to these events includes extended spring droughts, low live fuel moisture, low volumetric soil moisture, and severe fire weather conditions. Fire scars and callous formations in larger rainforest trees were present in all stands visited, and in some cases were only evident following tree collapse where the tree buttresses fractures and expose past fire scars. These multiple lines of evidence suggest that the rainforests of northern NSW have experienced fire repeatedly over an extended period and have an inherent degree of resilience to wildfires.

# INFORMING POST-FIRE RECOVERY PLANNING

Post-fire recovery planning and future risk planning for environmental assets is now undertaken with an understanding that we are already experiencing an overall increase in FFDI for southern and eastern Australia (Dowdy 2018) and that multiple scenarios are predicting a further increase in the FFDI and related climate metrics (CSIRO 2019, Dowdy et al. 2019). Concurrently, trends in increasing wildfire activity attributed to warmer and drier seasonal conditions in spring are being reported for temperate ecosystems globally (Westerling et al 2016, Pausas and Keeley 2021). This raises important concerns that anthropogenic climate change may overwhelm the resilience of forest ecosystems to climate variability and fire effects. Extreme climate events and wildfires are predicted to increase in frequency and intensity in coming decades (CSIRO 2020). This will necessitate new approaches to post-fire recovery planning. The challenge is that post-fire recovery planning is being undertaken as the fire-climate relationship is changing. For rainforests it may become increasingly difficult to maintain the fire-free intervals that they require to regenerate and recover from fire.

The 2019/20 wildfire season offers unprecedented opportunities to develop and apply new theory and practice to post-fire recovery planning for the rainforests of northern NSW. The scale and intensity of the wildfire event, the rapid development of bespoke remote sensing tools for measuring wildfire severity, extent and time-series recovery metrics, and the amount and depth of fire behaviour intelligence gathered by the fire-fighting authorities is unprecedented. Combining these approaches would permit post-fire recovery decisions to be informed by evidence of the ecological resilience for different rainforest formations, the impacts of wildfire events, the prospects for recovery, and where the predicted recovery trajectories warrant some intervention, the appropriate techniques for assisted recovery and monitoring.

The primary post-fire recovery decision support tool used in northern NSW is the Multi-Criteria Analysis Shell for Spatial Decision Support (MCAS-S model, MCAS-S Development Partnership 2018), which incorporates an expert elicitation process and spatially explicit risk assessment predictive model. Rainforest formations have spatially explicit risk models devised, informed by the tolerance, resilience or sensitivity of the canopy and understorey to fire, the pre-fire condition of the rainforest stands and an expert assessment of the consequence of fire to each rainforest formation. The spatial model aims to answer the question “What is the risk of decline or loss of the Gondwana Rainforest World Heritage Values post 2019-2020 fires?”

The MCAS model used to inform post-fire recovery planning in 2020 adopts a range of assumptions on rainforest tolerance, resilience or sensitivity to wildfire, and recovery time periods. These assumptions are developed using existing data and expert elicitation. The basis of the assumptions is variable and heavily weighted towards expert opinion and an understanding of vegetation traits. Rarely is empirical data from observational studies in northern NSW rainforests used to support the assumptions. Nonetheless, despite the acknowledged limitations of the expert elicitation process, the only mechanism to test and validate the spatially explicit risk assessment predictive model is the application of well-designed, on-ground monitoring studies. This study has utilized a range of long-term monitoring studies to establish the baseline conditions to test and validate the post-fire recovery decision support tool in one section of the Gondwana Rainforest estate, and has developed techniques that can be extended into other components of the Gondwana Rainforests.

Several premises require assessment as part of any post-fire recovery decision support analysis. The extent of the impacts of the fires in terms of area and severity differed across the Gondwana Rainforest estate and across the different rainforest formations. Overall fire impacts were most severe in Dry Rainforest and Northern Warm Temperate Rainforests. Whether this is due to intrinsic factors, landscape position, fire weather, or some combination of these requires further analysis. However, it is clear that all of the rainforests showed evidence of previous fire impacts with some stands having experienced fires in 2019, 2013, 1994, 1968 and potentially 1956. Monitoring of thousands of trees over the past 12 years has demonstrated that repeated fires can lead to the progressive weakening and eventual collapse of canopy dominants. Nonetheless, many large rainforest canopy dominant trees exhibited considerable resilience to repeated fire impacts and were able to maintain hydraulic conductivity and healthy crowns.

With the fire in the study area being primarily north and north-westerly runs, the implications are that the rainforest stands on the New England tablelands or on the edge of the tablelands towards the eastern fall are the most exposed to repeated fires, the activity of foehn winds, and long range spotting and ember attack. Rainforests in these landscape positions, particularly the smaller patches, showed evidence of ongoing attrition and a lack of regeneration. These stands historically have supported populations of the threatened Rufous Scrub-bird (*Atrichornis rufescens*), a vulnerable species which has exhibited an immediate post-fire decline. Burnt edges were colonised by rainforest pioneer species such as *Callicoma serratifolia* and *Persoonia media* in addition to short-lived semi-woody (*Solanum* spp.)and herbaceous species. Rainforest stands in these landscape positions are perhaps the most vulnerable to the ongoing impacts of fire and are also the most problematic to address for fire-risk planning. Rainforest stands further east are likely to have greater topographic protection within the sheltered aspects of the Great Escarpment, and may have persisted in these core habitat areas during the glacial and interglacial periods when rainforests would expand and contract across the landscape (Adam 2017, Hunter 2004).

Our results highlight predictable patterns of rainforest vulnerability to fire based on landscape position, rainforest type, and exposure to traditional fire paths. This provides fire planners with opportunities to use spatially explicit risk assessment and planning approaches to address this problem. Once the principles are developed around the vulnerability of particular rainforest formations and their exposure to repeated fires, rainforest stands, as environmental assets, can be categorised and treatments developed in a new dynamic risk-planning framework. Traditional risk management approaches designed to manage fuel hazards within the forest matrix will go some way towards addressing risk; however, the extensive nature of spotting and ember attacks suggests that management of fuel hazards around rainforest patches can only go so far in terms of ameliorating risk.

Long range (2-5 km) spotting and ember attacks were characteristic features of the 2013 and 2019 fire seasons in the study area. In most cases, ignitions resulting from long-range spotting only led to localised fires within rainforest. At times these fires only ignited individual larger sized trees with pronounced buttress hollows. While these small scale ignitions do not pose a significant risk to rainforest patches, they do represent a significant source of damage to the stands where they lead to a loss of condition. It was of significance that the larger older mature rainforest trees in this study appeared to be the most susceptible to ignition. This contrasts with most studies of fire-induced tree mortality, which have found that smaller trees are the most susceptible to fire. Considering very slow tree growth rates, the episodic nature of seedling regeneration, and the substantial age of most of the canopy dominants (> 300 years), the replacement of collapsed canopy dominant trees after fires will be a particularly slow process.

# RECOMMENDATIONS

1. *Establishing a Monitoring, Evaluation and Reporting system, and use that to establish a baseline dataset of forest conditions.*

The Gondwana rainforest estate requires a comprehensive, stratified, and systematically designed monitoring, evaluation and reporting framework to both monitor the effectiveness of ongoing management of the Outstanding Universal Values, support periodic condition reporting to the IUCN, and to provide a mechanism for informing recovery planning following events such as the 2019/20 wildfire season. Existing studies such as the long-term plot network managed by the first author provide a unique baseline for such a framework and provide the ability to hindcast rainforest conditions and dynamics in the context of decadal climate variability and repeated fires. A number of forest monitoring systems exist nationally or are being designed within NSW. These could be configured to focus on the Gondwana forest estate and the monitoring, evaluation, and reporting of key outstanding universal values. Several of these systems have recently developed hindcasting analytics for remotely sensed metrics including canopy cover and condition to 1990. These analytics provide the option of creating a baseline for a monitoring system from the time the Gondwana rainforest estate became a World Heritage-listed site.

- *A scoping paper is required to explore options for a Monitoring, Evaluation, and Reporting system that integrates multi-scale remotely sensed metrics, permanent ground-based monitoring sites and continuous public reporting via web-based dashboard analytics.*

2. *Develop a fire behaviour model for rainforests*

Fire behaviour models exist for the most fire-prone vegetation types in Australia. They are the basis of risk planning and prediction systems. Significantly reducing the likelihood of wildfire damage to the temperate rainforests of northern NSW will require an improved understanding of how rainforests respond to the four key drivers of wildfire events – the ignition source, fuel continuity, drought thresholds, and anomalous weather events such as foehn winds across the dissected terrain of northern NSW. The instantaneous weather conditions experienced on multiple occasions in spring 2019 pushed the thresholds for ignition, fuels, and drought down to create the conditions where rainforests burnt. Our ability to describe the impacts of the 2019/20 wildfire season on rainforests was constrained by our limited understanding of these four key drivers, the lack of a generalized fire behaviour model for rainforests, and poor understanding of how they respond to infrequent fire events. A fire behaviour model would quantity these drivers and lead to an improved understanding of fuel mass and dynamics, flammability characteristics, fuel moisture and fire weather conditions conducive to rainforests carrying a running fire, ignition probability from ember attack, fire line intensities and distances required to progress from a short to extended fire run condition This information will critically inform the options for continuing to use rainforests for natural containment, particularly during periods of low soil and fuel moisture.

- A scoping paper is required to explore options for developing a fire behaviour model for rainforests, jointly with Queensland, NSW, Victoria, and Tasmania, gathering lessons learned from fires seasons from 1983 in Victoria to present.

3. *Improving incident management planning and response*

The rainforests in northern NSW have been used as natural firebreaks (the *green fire strips* in Forestry Commission of NSW 1957) since the 1950s, a practice described by Cheal (2010) as leading to gradual destruction by attrition of rainforest margins. Fire managers became less reliant on this practice as the environmental significance of excluding fire from these stands became more widely accepted, and more recently, extended spring drought conditions meant these rainforest stands could not necessarily be relied upon for soft containment. Fire managers are now reporting litter fires transgressing rainforest stands despite the assumption that they would contain the fire run. While natural containment has significant advantages compared to bare earth approaches, the reliance of rainforests as natural containment options requires re-evaluation during periods of extended fuel moisture deficits.

- *A study is required to examine the relationship between rainforest type, patch configuration, and fire weather to explore why some rainforests burnt and others did not during the 2019/20 wildfire season. Wildfires can be 're-run' using Phoenix Rapidfire or SPARK under a range of fire behaviour conditions. The outputs will inform options for the continued use of rainforests for soft containment.*

4. *Improving rainforest mapping*

Multiple sources of rainforest mapping exist in NSW, from traditional aerial photographic interpretation to spatially modelled products constrained by structural vegetation types. These products differ and confound the challenge of describing the extent of the impacts of wildfire in rainforests. The different mapping products also introduce inconsistency in risk management and incident response planning. Fire managers typically adopt the mapping source they have most confidence in; in contrast, spatial modellers typically adopt the mapping source that aligns with their modelling information requirements. Initial public reporting of the extent of the 2019/20 wildfire event in NSW rainforests was confounded by the use of rainforest mapping sources that differed depending on the user. The results of this study underscore the importance of a single agreed baseline for rainforest mapping. A possible way forward for merging both traditional photo-interpreted rainforest mapping with more recent spatially explicit modelling would be to constrain the spatial model with a LiDAR-derived structural rainforest map and use that as the basis of a novel spatially modelled plant community type map. This approach will involve some exploration, but has recently been developed in Victoria (Trouve et al. unpublished).

- *A study is required to pilot a method of rainforest structural mapping at the NSW Formation or Vegetation Class level that meets land managers spatial accuracy and typology expectations to support incident response.*

5. *Lessons learned workshop or After Action Review*

Patterns are emerging regarding the thresholds that must be crossed for rainforests to either ignite or sustain a running fire. There are also lessons to be learned from the effectiveness of the response process and immediate impact assessments and how the short- to medium-term monitoring of impacts and recovery has been managed. Seeing the considerable resources committed to emergency response processes and the post-fire recovery planning, It is perhaps surprising that no focused workshop has yet been convened on rainforests and their response to wildfires, particularly considering that the frequency of these events appears to be increasing since the 2009 fires in Tasmania. To be most effective the workshop should be convened by a facilitator with experience in expert elicitation. The workshop would identify if there is a consensus among experts on the fire thresholds for rainforests and the implications for rainforest ecology.

- *Convene a facilitated workshop of land managers, fire behaviour modellers, and rainforest ecologists to share fire intelligence observations and post-fire recovery data from rainforest fires in Queensland, NSW, Victoria, and Tasmania in recent decades.*

6. *Improving fire extent and severity mapping and development of canopy recovery metrics in rainforests*

The 2019/20 fire season saw very significant improvements in remotely derived fire severity metrics. However, low-intensity fires in rainforests, especially those exhibiting canopy drought reflectance signatures, were challenging to capture. Techniques exist to iteratively improve the modelling; however, these require the collection of ground validation data and potentially the integration of other remotely sensed data (both spectral and spatial).

- *A study is required to support the ongoing improvement of fire extent and severity mapping in rainforests, and the development of canopy recovery metrics to measure post-fire recovery rates and trajectories.*

7. *Improving our understanding of short- to medium-term patterns of rainforest post-fire tree regeneration, recovery, and collapse.*

Our study has reported on the immediate impacts of wildfires on rainforest post-fire tree regeneration, recovery, and collapse. We demonstrate that lag effects exist where tree regeneration can fail or mortality rates increase over time as canopy dominants succumb to fire damage and structural and hydraulic failure. The existing study plots require periodic re-measurement to quantify how long the fire continues to impact rainforest dynamics. A single post-fire assessment will miss substantial lagged mortality associated with the fire. Extending the current study and supporting measurement plots established by other groups in different sections of the Gondwana rainforest estate would permit a broader understanding of the impacts of the 2019/20 wildfire season.

- *A scoping paper is required to explore options for supporting the periodic re-measurement of rainforest post-fire monitoring plots to better understand the long-term consequences of fire impacts on rainforest. This could potentially be integrated into a broader Gondwana Rainforest Monitoring, Evaluation, and Reporting system and support the development of an improved rainforest post-fire canopy recovery metric.*

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## Appendix 1 Tree and plot measurement attributes and codes.

| | |
|---|---|
| Plot_No | sorting key |
| plot_ID | locality description |
| Zone | |
| Easting | GPS |
| Northing | GPS |
| Latitude | GPS |
| Longitude | GPS |
| Elevation (m) | GPS |
| plot size (ha) | 30*30 m (burnt) or 40*40 m (unburnt) |
| Date | date sampled |
| tree_id | note trees are not being tagged but are measured in a sweeps |
| Tree dominance | dom = in upper canopy on its own, trees whose crowns are above the general level of the canopy and enjoying full light from above, and to obtain from all sides |
| | co dom = in upper canopy in a group, trees which are not as tall as the dominant but which have excellent one lead light are large crowned, rapid growing, and in no danger of being crowded out by the dominants |
| | sub dom = sub-dominant on its own or in a group, crowns of intermediate trees are usually rather narrow and they occupy rather small holes in the canopy. In an undisturbed forest they are usually finally overcome by the closing crowns of dominant and co-dominant trees |
| | suppressed = poor form, beneath sub-canopy, suppressed trees are definitely below the general level of the canopy and have no full overhead light at all. They exist by light that filters through the crowns of large trees and sometimes by light from the sky reaching them a break in the canopy |
| burnt (y/n) | evidence of buttress, trunk or canopy charing or scorch |
| FESM class per Sentinel 2 pixel (U, L, M, H, E) | https://datasets.seed.nsw.gov.au/dataset/fire-extent-and-severity-mapping-fesm |
| FESM class per tree (U, L, M, H, E) | U = unburnt |

| | |
|---|---|
| | L = low severity (burnt understory, unburnt canopy) |
| | M = moderate severity (partial canopy scorch) |
| | H = high severity (complete canopy scorch, partial canopy consumption) |
| | E = extreme (full canopy consumption) |
| mortality | no sign of living tissue, ie no coppice response |
| dbh (cm) | 1.3 m unless identified as buttressing then alternate ht measurement point given in notes |
| tree ht (m) | top ht. For collapsed trees ht was measured on the ground following the fallen bole and crown to estimate pre-fire height prior to collapse. |
| char ht on bole or canopy (m) | char ht |
| extent of buttress charring | nil, low, moderate, high as a proportion of trunk area |
| % canopy scorch | % of canopy foliage |
| tree health | very poor, poor, fair, good |
| tree collapse | on ground usually from buttress failure |
| pre-existing damage | damage prior to burning, eg dry side, buttress damage, buttress hollows. Categories are nil, low, moderate, high |
| post-fire regeneration | basal coppice (BC) |
| post-fire regeneration | stem coppice (SC) |
| mode of regeneration | canopy coppice (CC) |
| post-fire regeneration | seedling (SEED) |
| post-fire regeneration | nil |
| post-fire regeneration abundance | nil, low, moderate, high |
| COMMENTS | as per observer |
| Species code | species |
| BBA | Elaeocarpus reticulatus |
| BLW | Acacia melanoxylon |
| CAL | Callicoma serratifolia |
| CDW | Acacia elata |
| CKW | Ackama paniculata |

| | |
|---|---|
| CRA | Schizomeria ovata |
| CWD | Ceratopetalum apetalum |
| GPS | Quintinia verdonii |
| GSF | Doryphora sassafras |
| INT | Banksia integrifolia |
| LPY | Acmena smithii |
| MM | Eucalyptus obliqua |
| MWN | Cryptocarya foveolata |
| NEB | Eucalyptus andrewsii |
| NHB | Nothofagus moorei |
| PSH | Orites excelsus |
| PSW | Quintinia sieberi |
| SPT | Pittosporum undulatum |
| TLG | Persoonia media |
| TRC | Tristaniopsis collina |
| TWL | Cryptocarya meissneriana |
| YCB | Sloanea woollsii |