Knowing why Tasmanian *Eucalyptus obliqua* tall forests are so sensitive to heatwaves informs management and policy for climate change adaptation

Timothy J. Wardlaw[a]*

[a] *Climate Futures & School of Natural Sciences, University of Tasmania, Hobart, Australia.*

*corresponding author (timothy.wardlaw@utas.edu.au)

Abstract

Tasmania's distinctive climate environment supports highly productive and carbon-dense tall eucalypt forests, but also a vulnerability to climate change. Measurements in *Eucalyptus obliqua* tall forest at the Warra SuperSite in southern Tasmania showed them to be very sensitive to warmer temperatures. Gross primary productivity (GPP) declines sharply when temperatures rise above the forest's relatively low temperature optimum for GPP. Heatwaves (consecutive days of unusually high temperatures) cause the forest to switch from being a net carbon sink to a net carbon source. As the climate changes and heatwaves occur more often, the risk of severe adverse impacts to this important ecosystem increases. Our current understanding of why the Tasmanian *E. obliqua tall* forest is so sensitive to warmer temperatures, even if imperfect, can allow appropriate management interventions to be identified and enabling policy settings to be formulated.

Tasmania's climate environment was associated with several features of the unique response by the tall eucalypt forests to heatwaves. The high sensitivity of GPP to temperature in the forest was associated with a low temperature range – GPP sensitivity to temperature increased as temperature range experienced by the forest decreased. The decline of GPP during warm conditions was not associated with either moisture limitation or atmospheric dryness (high vapour pressure deficits), a likely reflection of the high rainfall environment in which tall eucalypt forests grow in Tasmania. Low winter radiation associated with Tasmania's high latitude, contributes to a lack of seasonal temperature acclimation by the forest. Because the forest responses to heatwaves were associated with the local climate environment, enhanced natural selection of local genotypes is identified as the most prospective approach to help Tasmania's tall eucalypt forests adapt to a new, warmer climate. Enhanced natural selection is only feasible to do in forests that are managed for wood production. Policy settings that allow for the continuation of native forest harvesting will be needed if enhanced natural selection is to supply future needs of climate-adapted seed for regeneration and restoration of tall eucalypt forest areas in Tasmania.

Keywords: *Eucalyptus*, heatwave, climate change adaptation, carbon dynamics, forest policy

Introduction

Tasmania has approximately 800,000 ha of tall eucalypt forests restricted to the high rainfall areas of the state (Forest Practices Authority 2023). The largest concentration is in a narrow band extending from the northwestern corner of the state to the south-east coast (Harris and Kitchener 2013). The tall eucalypt forests are dominated by three species – *Eucalyptus obliqua, E. regnans* and E. *delegatensis*. Forests dominated by *E.*

obliqua are the most widespread of the tall eucalypt forest type (Neyland et al. 2000). Tall eucalypt forests are well represented in both conservation reserves and areas available for timber harvesting (Forest Practices Authority 2018). These forests are very productive in both an Australian context (Beringer Jason et al. 2016; Bennett et al. 2021) and globally (UNESCO et al. 2021). Their high productivity coupled with a temperate climate, results in the forests accumulating very high biomass (Keith et al. 2009; Moroni et al. 2010; Wood et al. 2015). The value of Tasmania's tall eucalypt forests for removing CO_2 from the atmosphere is reflected in UNESCO identifying the Tasmanian Wilderness World Heritage Area (TWWHA) as their number one property, globally, in terms of the amount of carbon sequestered annually by forests (UNESCO et al. 2021).

A warming climate is jeopardising the high productivity and accumulated biomass of Tasmania's tall eucalypt forests (Bowman et al. 2014, Prior and Bowman 2014). Heatwaves are particularly impactful. During a record heatwave event in November 2017, the *E. obliqua* tall forest at the Warra SuperSite within the TWWHA switched from being a net carbon sink to become a net carbon source (Wardlaw 2022). The switch from a carbon sink to a source was due to significant reductions in gross primary productivity (GPP) of the forest when compared with periods of closer-to-normal temperatures. This heatwave response contrasts with those in other non-water-limited temperate eucalypt forests on the Australian mainland. Griebel et al. (2020) found no change in GPP of an *E. obliqua* / *E. radiata* forest in central Victoria during a heatwave event, while (van Gorsel et al. (2016) found that GPP slightly increased during a heatwave event in an *E. delegatensis* / *E. dalrympleana* in southern NSW.

The contrasting responses to heatwaves in these eucalypt forests reflects differences in the relationship between GPP and temperature. A convex parabola (upside-down "u") represents the general relationship between GPP and temperature of vegetated ecosystem (Bennett et al. 2021, Duffy et al. 2021). The apex of the parabola represents the temperature when the GPP of the ecosystem reaches a maximum – the optimum temperature for GPP. The steepness of the curves either side of the apex represents the rate that GPP declines as temperatures depart from the optimum for the ecosystem - the sensitivity of the ecosystem to changes in temperature. GPP of the Tasmanian tall eucalypt forest was more sensitive to changes in temperature than was GPP for the Victorian and NSW forests (Bennett et al. 2021). The high sensitivity of GPP to temperature in the Tasmanian tall eucalypt forest was more like that of tropical rainforest and tropical savanna forest in their wet season than it was for other temperate eucalypt forests and woodlands.

Duffy et al. (2021) point out that the carbon balance of ecosystems represents the combined effect of two components: GPP, which varies parabolically with temperature; and ecosystem respiration, which increases exponentially (i.e. at an ever-increasing rate) with temperature across the range of temperatures capable of supporting life. As temperatures rise above the optimum for GPP, the carbon balance of the ecosystem quickly declines. This is because the decline in GPP is reinforced by the increase in respiration. A point is reached when temperature rises too much above the GPP optimum that the carbon balance of the ecosystem becomes negative– the ecosystem starts to lose carbon (i.e. it becomes a carbon source). As global warming progresses ecosystems will have a negative carbon balance for an increasing proportion of the time. Duffy et al. (2021) predict a warming-induced tipping point when the current generation of plants in an ecosystem can no longer recover from a negative carbon balance. A persistent negative carbon balance from crossing such a tipping point is expected to lift the rate of tree mortality despite uncertainty about the mechanism(s) causing tree death (Wang et al. 2021). Many ecosystems, mostly tropical, could reach a temperature tipping point within three decades (Duffy et al. 2021). Tasmania's tall eucalypt forests in being like tropical forests by having a high sensitivity of GPP to temperature, may reach a temperature tipping point earlier than other temperate eucalypt forests.

Management intervention needs to be planned and developed to reduce or avert the adverse consequences of warming temperatures to Tasmania's value-laden, tall eucalypt forests. Developing effective interventions will require a diagnosis of why Tasmania's tall eucalypt forests show such contrasting responses to temperature and heatwaves than other temperate eucalypt forests.

Tasmania's distinctive environment (Thackway and Cresswell 1995) can make it challenging to diagnose causality of syndromes affecting forest health. Spring needle cast of *Pinus radiata* is a good example: a widespread needle-infecting fungus, *Cyclaneusma minus*, is triggered into secondary pathogenic activity on high altitude (>400 metres), wet (>1200 mm annual rainfall) sites (Podger and Wardlaw 1990). A successful tree breeding program to identify *P. radiata* genotypes resistant to spring needle cast focussed on the expression of disease on high altitude – wet sites, rather than directly on resistance to the needle-infecting pathogen *C. minus* (Kube and Wardlaw 2002a; Kube and Wardlaw 2002b). A confident diagnosis of causality is needed to explain the unique response to heatwaves seen in Tasmania's tall eucalypt forests as a first step towards developing climate adaptation actions.

The Terrestrial Ecosystem Research Network – TERN - (www.tern.org.au) infrastructure provides extensive data that measures attributes of Australia's main terrestrial ecosystems. Those data can be used for detecting and understanding change in those ecosystems. TERN SuperSites (Beringer Jason et al. 2016; Karan et al. 2016) provide detailed, local-scale measurements, both as continuous timeseries and from hosting designed experiments. The continuous timeseries can detect change in ecosystems that occur during extreme events like heatwaves (e.g. van Gorsel et al. 2016), droughts (e.g. Keith et al. 2012; Ma et al. 2016) and fire (e.g. Sun et al. 2020; Wardlaw 2021). One of the 16 TERN SuperSites – the Warra Tall Eucalypt SuperSite – is embedded in *E. obliqua* tall forests within the TWWHA. Measurements at that site identified the threat that warming temperatures, and heatwaves pose to this ecosystem.

Here I review research findings from measurements made at Warra and other TERN SuperSites, as well as other published studies, to characterise the unique response to heatwaves shown by Tasmanian tall eucalypt forests. A putative diagnosis of causality will be made through synthesis of those unique responses. The putative diagnosis will then be evaluated against possible management options to determine the most suitable option to use in helping tall eucalypt forests adapt to the new climate. Finally, I will review policy settings for management of tall eucalypt forests in Tasmania to identify how well settings align with management option that result in future forests that are better suited to Tasmania's new climate.

Characterisation of unique responses in Tasmanian tall eucalypt forests

Association between changes in GPP and regulation of water loss

In many eucalypt forests, stomatal regulation to limit water loss is a dominant driver of declines in GPP during hot conditions (van Gorsel et al. 2016, Renchon et al. 2018, Beringer et al. 2022), although leaf loss to limit transpiration has also been linked to productivity declines (van Gorsel et al. 2013, Renchon et al. 2018).

In wetter environments where moisture limitation is rare, GPP of the eucalypt forests show negligible change during hot conditions (van Gorsel et al. 2016, Griebel et al. 2020). The tall eucalypt forests of southern Tasmania behave differently. During a record heatwave event in 2017 the GPP of *E. obliqua* tall forest at Warra in southern Tasmania declined sharply, but that decline in GPP was not associated with stomatal regulation to limit water loss (Wardlaw 2022).

The heatwave response suggests the tall eucalypt forest ecosystem in southern Tasmania exerts little control to limit water loss. Several independent lines of evidence support limited regulation of water loss in these forests. Peters et al. (2021) found that canopy-forming *E. obliqua* and understorey trees at Warra had low hydraulic safety margins, like tropical rainforests. Salvi et al. (2021) found young *E. obliqua* saplings showed the lowest degree of stomatal regulation to limit water loss among the ten eucalypt species they examined: maintaining high rates of photosynthesis was a more important life strategy than conserving water. Two other eucalypt species – *E. regnans* and *E. nitens* - whose natural range are confined to mesic sites, behaved in a similar way. The threshold response of stomata to increasing water stress in *E. obliqua* saplings found by Salvi et al. (2021), matched a threshold response of stomata to increasing VPD (Figure A1). This threshold response was measured in 70-years-old *E. obliqua* regrowth at Hastings, southern Tasmania, during the hottest day on record in southern Tasmania on 15th February 1982. Measurements of changes in soil water content of the *E. obliqua* forest at Hastings by Nicolls et al. (1982) found high rates of water loss via transpiration were sustained over long periods of time. Such high rates of water loss only matched model predictions of soil dryness if the soil dryness model was adjusted to maintain maximum transpiration rates rather that declining rates of transpiration as the soil became drier.

Role of optimum temperature for productivity

Might a low optimum temperature for GPP explain the strong reduction in GPP at high temperatures in southern Tasmania in contrast with other eucalypt forests during non-water-limited conditions on the Australian mainland? Bennett et al. (2021) showed that the temperature optimum for GPP was related to the historical temperature of the site. But the temperature optimum for GPP at Warra was within the range of other tall eucalypt forests on the Australian mainland (Figure 1). What does differentiate the tall eucalypt forest at Warra from those on mainland Australia is the steepness of the decline in GPP as temperatures depart away from the optimum (Figure 1).

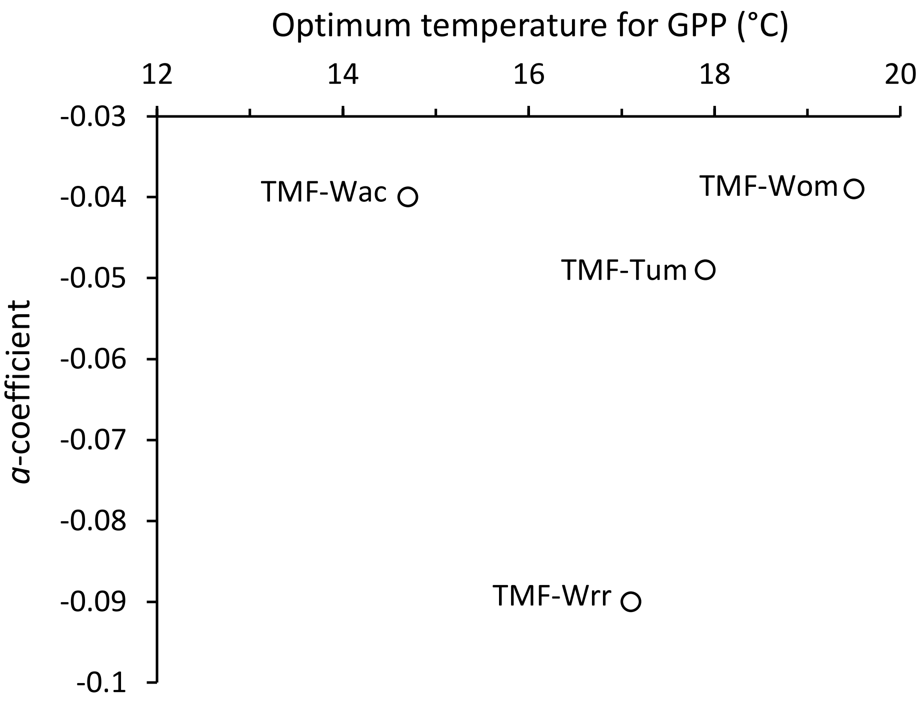

Figure 1. Scatterplot of temperature optimum for GPP and the *a*-coefficient (defining steepness of curve) of the binomial model describing the parabolic relationship between GPP and temperature of four temperate eucalypt forests. Data extracted from Table 2 in Bennett et al. (2021). Sites shown are: Wallaby Creek (TMF-Wac), Warra (TMF-Wrr), Tumbarumba (TMF-Tum) and Wombat Forest (TMF-Wom).

Seasonal temperature acclimation

The capacity of ecosystems to acclimate to changed temperature regimes can reduce the sensitivity of their carbon dynamics to those temperature changes (Smith et al. 2015). There is some evidence that forest and woodland ecosystems on the Australian mainland can adjust the temperature dependence of their photosynthetic and respiratory activity in response to the contrasting temperature regimes that occur in the winter and summer (Zhu et al. 2018, Zhu et al. 2021). This is reflected in significantly higher tree respiration rates at a common reference temperature of 25°C, but lower maximum rates of respiration, for measurements done in winter compared with measurements done in the summer (Table 1). Similarly, the critical temperature for photosynthesis increased during the summer measurements compared with winter measurements (Table 1). In contrast, forest species at Warra showed no evidence of adjustment in respiration rates at 25°C or critical temperature for photosynthesis between winter and summer (Table 1). Zhu et al. (2021) attributed the lack of seasonal acclimation in respiration rates at Warra to insufficient solar radiation in the winter. Tasmania’s high latitude, coupled with high cloudiness in the wetter parts of the state each contribute to the low winter radiation (Grose et al. 2010).

Site	Warra	Cumberland Plains	Great Western Woodlands	Alice Mulga	Robson Creek	Cape Tribulation
Respiration rate @25°C	↓*	↑*	↑*	↑	↑*	↑*
Maximum respiration rate	↔	↓*	↓*	↓*	↓*	↓*
Critical temperature for photosynthesis	0.04_{a} (0.02)	$0.2_{a,b}$ (0.06)	0.52_{b} (0.09)	$0.22_{a,b}$ (0.08)	0.51_{b} (0.13)	-

Table 1. Seasonal (Winter-Summer) differences in respiration rate at 25°C, maximum respiration rate, and critical temperature for photosynthesis at six TERN SuperSites. For respiration rate at 25°C, up arrows indicate higher rates in winter than summer, and for maximum respiration rates, down arrows indicate lower rates in winter than summer (asterisks indicated significant differences between the seasons). The values for critical temperatures for photosynthesis indicate the increase in critical temperature for photosynthesis in summer compared with winter, expressed as °C difference in critical temperature per degree difference summer and winter ambient temperatures. Data for respiration rates adapted from Figure 3a and Figure 3d in (Zhu et al. 2021). Data for critical temperature for photosynthesis (with standard error shown in parentheses) adapted from Table 2 in (Zhu et al. 2018).

Temperature range

The unusually high sensitivity of GPP to temperature in the tall eucalypt forest at Warra is an outlier among temperate eucalypt forests (Figure 1). This high sensitivity is similar to tropical rainforests and tropical savanna forests during their wet season (Bennett et al. 2021). No analysis has been done to try and explain these differences in the sensitivity of GPP to changes in temperature.

In one of the very few studies done to examine variation in the sensitivity of GPP to temperature, Wu et al. (2017) found the temperature sensitivity of GPP in northern hemisphere vegetated ecosystems decreased as the variability in growing season temperature increased. Can characteristics of the temperature regime of the site explain the sensitivity of GPP to temperature?

Bennett et al. (2021) reported seasonal temperature ranges for the 17 forested sites in Australia used to calculate their GPP - temperature response function. This provided an opportunity to examine the relationship between seasonal temperature range and the sensitivity of GPP to temperature for those sites. To do this the annual or seasonal temperature range was extracted from Figures 2 and 4 in Bennett et al. (2021) and plotted against the a-coefficient of the binomial model of GPP ~ temperature (from Table 2 in Bennett et al. (2021)) that was fitted to the 17 sites they were analysed. Data from the five tropical savanna sites were excluded from the analysis because of the confounding effect of C4 grasses that dominate productivity in their wet season (Moore et al. 2018).

The plot of the a-coefficient of the binomial model and annual temperature range for each of the 12 non-savanna sites shows the sensitivity of GPP to temperature (a-coefficient) increases as the temperature range decreases (Figure 2). This result is consistent with the findings of Wu et al. (2017). The temperature range for Warra may be lower still if seasonal factors that limit GPP occur regularly. For example, a latitudinally-driven limitation in radiation during winter that suppresses seasonal temperature acclimation (Zhu et al. 2021) may also suppress GPP. Temperate forest sites at lower latitudes on the Australian mainland do not have such a winter radiation limitation. This provides those sites the flexibility to capitalise on more equable climatic conditions for carbon uptake in winter, e.g. Renchon et al. (2018).

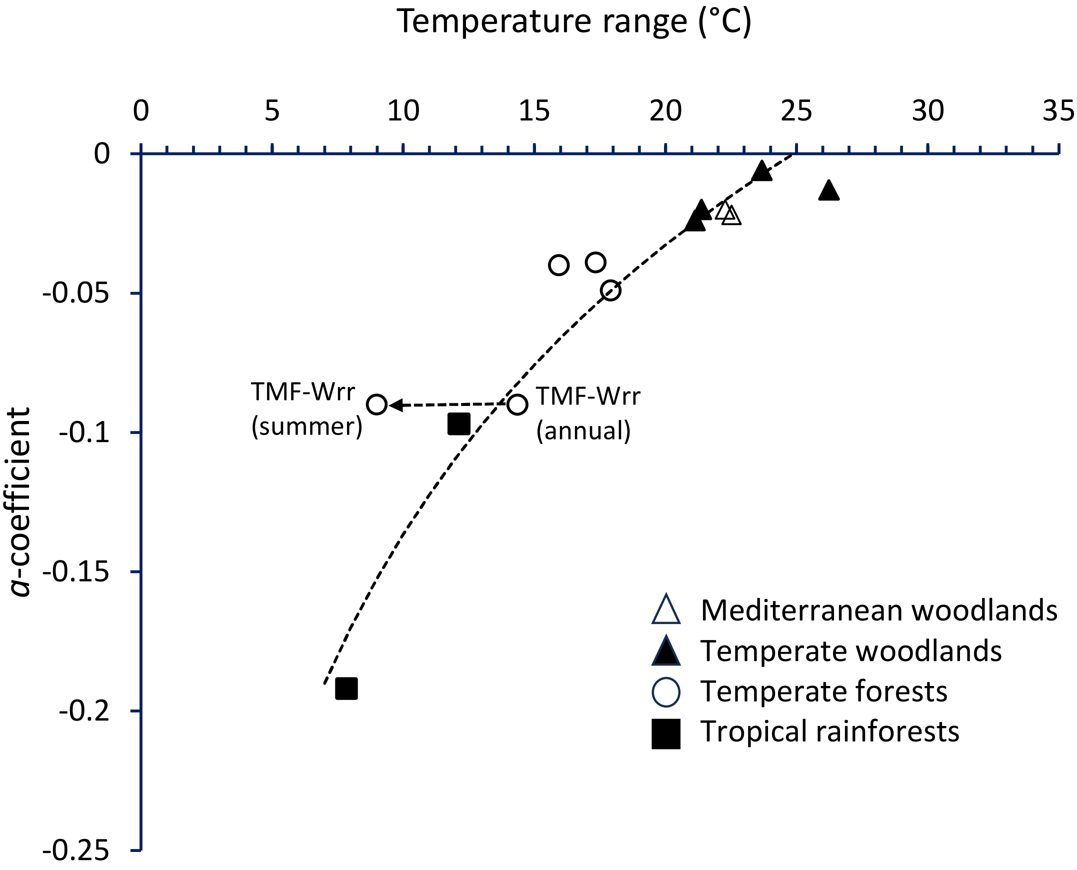

Figure 2. Plot of the relationship between the a-coefficient of the GPP versus temperature binomial model and annual / growing-season temperature range of 12 forested sites representing four Australian ecosystems. For the Tasmanian site (TMF – Wrr) two values are shown for temperature range: an annual range and a summer range that excludes winter data in accordance with a radiation limitation identified by Zhu et al. (2021). The dashed line shows the fitted model: a-coefficient = -0.482 + 0.15 Ln(Temperature range).

A narrow temperature range is a plausible explanation for the higher sensitivity of GPP to temperature in the tall eucalypt forest at Warra. That explanation is consistent with the findings from the limited studies done elsewhere. A more confident diagnosis of causality will also need measurements be done in other tall eucalypt forests elsewhere in Tasmania to confirm that the effect measured at Warra is general. Finally, the mechanism through which a narrow temperature range increases the sensitivity of GPP to changes in temperature needs to be discovered.

Synthesis of responses and proposed diagnosis

A strong decline of GPP during heatwave events during non-water-limited periods is the effect that differentiates the tall eucalypt forest in Tasmania from those on the Australian mainland. Stomatal regulation to limit water loss was not associated with the strong decline of GPP in the Tasmanian tall eucalypt forest. Neither could the strong decline of GPP in the Tasmanian forest be explained by a low optimum temperature (for GPP), per se. Instead, the strong decline in GPP was the result of a high sensitivity of GPP to temperatures that exceed the optimum for GPP. The high sensitivity of GPP to temperature could be explained by the comparatively low temperature range of the Tasmanian forest. The temperature range may be narrowed further if the growing season is restricted by recurring seasonal limitations such as winter radiation.

Alignment of adaptation options to the proposed diagnosis

An effective adaptation response would seek to preserve the distinct traits of Tasmania’s tall eucalypt forests, notably their high growth rates, while lessening the risks imposed by a warming climate. Two traits likely to be contributing to the exceptional productivity of the tall eucalypt forests are: (i) maintaining high rates of photosynthesis for as long as possible by sacrificing control of water loss via stomatal adjustment (Nicolls et al. 1982, Salvi et al. 2021); (ii) peak rate of photosynthesis that is high but confined to within a narrow temperature range bounding the optimum temperature for photosynthesis (Bennett et al. 2021). The best way to maintain these traits while lessening the risks imposed by a warming temperature would be for the optimum temperature for GPP to increase as the climate warms, and for rainfall to remain high.

Bennett et al. (2021) showed the optimum temperature for GPP was linearly related to the historical temperature of the site. Temperature is rapidly increasing in Tasmania as elsewhere (CSIRO and Bureau of Meteorology 2022). It is not known whether the historical temperature reflects the temperature experienced over long periods of time (e.g.Vizcaino-Palomar et al. 2020) or temperature experienced at critical stages of forest development (de Araujo et al. 2019). Rainfall has decreased in Tasmania over the past four decades Grose et al. (2010), but most of that decrease has been during autumn months when soil moisture in tall eucalypt forests are at an annual nadir (Nicolls et al. 1982).

Three adaptation options are evaluated for their potential to lessen the climate risks to the tall eucalypt forests while preserving their distinctive traits.

Temperature acclimation

Temperature acclimation of the existing tall eucalypt forests to reduce the impact of a warming climate would be an ideal no regrets outcome. Smith et al. (2015) propose that temperature acclimation of photosynthesis and respiration could provide considerable benefit through reducing the sensitivity of carbon uptake to changes in temperature. The evidence from measurements done in the forests at Warra is that, unlike sites on the Australian mainland, they do no acclimate to the contrasting temperature environments in summer and winter (Zhu et al. 2018, Zhu et al. 2021): a consequence of low winter radiation (Zhu et al. 2021). Further, a capacity to acclimate to contrasting temperature environments does not translate to acclimation at longer (decadal) time scales (Duffy et al. 2021).

Climate adjusted provenancing (Assisted migration)

Climate adjusted provenancing is one of the most common approaches for accelerating forest adaptation to climate change (Prober et al. 2015, Prober et al. 2019, Booth and Muir 2020). The approach involves introducing into a target area, climate-adapted genotypes that evolved in those parts of the species range that are a climate analogue of the predicted future climate of the target area. Rainfall and/or temperature are typically used to determine climate analogues for the future climate of target areas (e.g. Drake et al. 2017, Sáenz-Romero et al. 2020, Harrison 2021). Neither of those environmental drivers contributed to the strong decline in GPP measured in the tall eucalypt forest at Warra during a heatwave event.

A climate analogue that is determined by rainfall and/or temperature may have difficulty in also meeting the distinctive traits associated with high forest productivity. Genotypes from warmer and drier regions are more likely to have evolved in temperate environments with wider temperature range and lower peak GPP, like those exhibited by temperate forests on the Australian mainland (Bowman et al. 2014, Bennett et al. 2021). Another issue would be that genotypes from warmer and drier environments would need to be sourced beyond the cool, moist band in the western half of Tasmania - the stronghold of tall eucalypt forests in Tasmania (Harris and Kitchener 2013). Populations of *E. obliqua, E. regnans* and *E. delegatensis* in that main western Tasmanian band are distinctive from populations elsewhere in southeastern Australia as shown by their chloroplast DNA (Nevill et al. 2009, Bloomfield et al. 2011, Nevill et al. 2014). Transfer of seed outside the western Tasmanian haplotype zone of those three eucalypts would need to consider the implications of disrupting the historical patterns of genetic diversity in these species (Bloomfield et al. 2011).

Maladaptation to local pests and pathogens can seriously impair the survival and growth of non-local genotypes in the target area (Wardlaw and Palzer 1988, Camarretta et al. 2020, Sáenz-Romero et al. 2020). The western Tasmanian band of tall eucalypt forests are concentrated in hotspots for epidemic Teratosphaeria (syn. Mycosphaerella) Leaf Disease (Pinkard et al. 2010) and local populations have strong adaptations to this group of leaf pathogens (Wilkinson 2008) . These co-incident threats to non-local genotypes of these tall forest eucalypts are likely to be a severe constraint to successfully introducing them into target areas as analogues for future climates.

In summary, climate adjusted provenancing would be an unsafe adaptation option for use in Tasmania’s tall eucalypt forests. Climate adjusted provenancing: would be unlikely to preserve key traits associated with high productivity; would disrupt historical genetic patterns in the main tall eucalypt species; and would increase the risk of damage from maladaptation to local pest and pathogen populations.

Enhanced natural selection

The proposed diagnosis of causality for the high sensitivity of GPP to temperature in Tasmanian tall eucalypt forests aligns well with natural selection in local forest populations. This is because natural selection in local populations would be expected to preserve evolved traits linked to local environment of the western band of tall eucalypt forests - small temperature range and high rainfall. In the western band of Tasmania’s tall eucalypt forests the predicted change in rainfall through the 21st Century due to global warming is small (Grose et al. 2010). There is a rise of 0.5-1°C predicted in summer temperature range (White et al. 2010) over the 21st Century. While a rise of that magnitude would give Warra a similar annual temperature range as other temperate forests, the growing season temperature range for Warra would still be well below other temperate forests as winter radiation limitations in western Tasmania would remain through the 21st Century (Grose et al. 2010). Natural selection in local populations would also retain historical genetic patterns in the main tall eucalypt species and adaptations to local pest and pathogen populations.

Evolution of adaptive traits as a response to climate change has been shown to confer advantages in fitness to plant and animal species (Rauschkolb et al. 2022, Moiron et al. 2024). These examples show that evolution of adaptive traits can occur quickly (1-2 decades) in natural situations for short-lived species. Enhancing natural selection using techniques such as managing for shorter generation times and screening to select adapted / cull non-adapted genotypes (Prober et al. 2019) may be needed for forest species that have longer generation times.

Evidence that evolution of adaptive traits is occurring in Tasmania's tall eucalypt forests as a response to climate change is lacking. Temperature and rainfall conditions during the first season of regeneration exert strong selection pressures in survivorship of *E. regnans* and *E. delegatensis* (Singh et al. 2021). Bloomfield et al. (2011) postulated that such selection pressure would establish adaptive patterns in each *E. obliqua* generation. An increase in the optimum temperature for growth is an adaptive response we might expect to see in response to a selection pressure imposed by unusually high temperatures experienced during the first year of regeneration. Obtaining measurements ‘to determine optimum growth temperatures would require sampling many sites to detect a significant effect. This would be impractical using eddy covariance (as in Bennett et al. 2021) but tractable using biometric methods such as dendrometry (e.g.Zweifel et al. 2021).

Forest growth rates obtained biometrically can show good agreement with those obtained by eddy covariance (Fenn et al. 2014, Dukat et al. 2021), although not always (Griebel et al. 2017). There are good prospects that biometry and eddy covariance would be in good agreement for Tasmania’s tall eucalypt forests. This is because most of the growth change measured by biometry is likely to be concentrated in the main stem that is easy to measure using dendrometers. Tall eucalypt forests would be expected to have low root:shoot ratios based on Mokany et al. (2005) who found root:shoot ratios decreased with increasing stand height, total biomass and total rainfall (all high in Tasmanian tall eucalypt forests). Furthermore, Ximenes et al. (2008) found a high proportion of the aboveground biomass in *E. obliqua* in a tall forest at Warra was concentrated in the main stem.

Because of the argument outlined in the previous paragraph, there is a strong prospect that dendrometry would enable a determination of variation in optimum temperature for growth be made from a sample of tall eucalypt forests throughout Tasmania. Many tall eucalypt forest stands have been regenerated each year by sowing after harvesting and burning of the logging slash since the mid-1960s in Tasmania. Screening these regenerating stands according to the temperature environment they experienced during their first year of growth would provide the basis of selecting stands with contrasting temperature regimes. For example, in the southern Forests (tall eucalypt forests southeast of the Huon River) stands regenerated in 1972, 1980 and 1989 experienced unusually high temperatures in their first year of growth, while stands regenerated in 1984, 1991 and 1994 experienced unusually low temperatures in their first year of growth. Installing a dendrometer network that sampled stands from the southern forests regenerated in the three hot years and the three cold years should provide an opportunity to measure the quantum of adaptation to warmer temperatures in one generation.

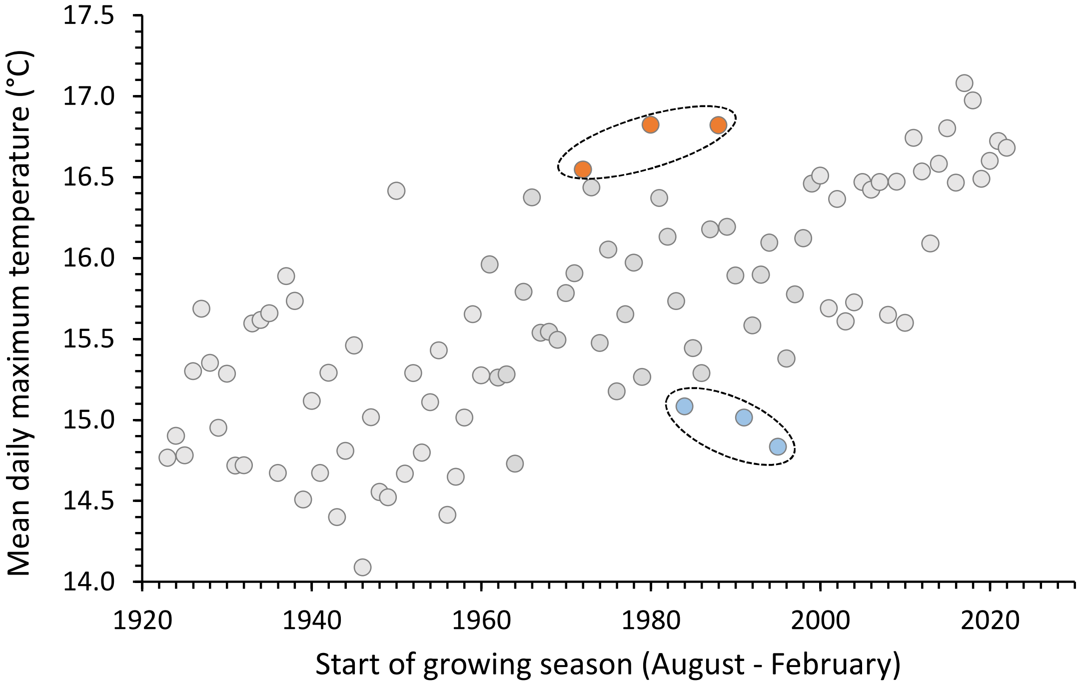

Figure 3. Plot of mean daily maximum temperature of the growing season (August-February) measured at Cape Bruny Lighthouse (Bureau of Meteorology station 94010). In the first three decades of clearfall, burn and sow silviculture (1970-1999) three unusually hot years are shown with orange fill and three unusually cold years are shown with blue fill.

Enhanced natural selection as described above requires a critical stage of regeneration (seedling stage) to coincide with a selection event (hotter than normal temperatures). Regeneration following natural disturbance by a high severity bushfire in tall eucalypt forests is a rare event in Tasmania, even after factoring in climate change (Furlaud et al.

2021). Thus natural selection events driving adaptation to a warmer climate will be very rare for natural disturbance. As a result, adaptation would be too slow to be of any benefit in generating future tall eucalypt forests that are better suited to the new climate we are rapidly moving towards. Tall eucalypt forest areas managed for wood production, by contrast, generate disturbance events every year, so there will be some regeneration at the critical stage of development every year a selection event occurs. Significant flowering and seed production begins once tall eucalypt forests reach about 25 years of age (Ashton 1975). Areas managed for enhanced natural selection could therefore enable several generations of natural selection to occur over, say, the next century. This may be sufficiently fast to generate future forests can persist in the new Tasmanian climate.

Policy settings to enable management for adaptation

Several Australian states have ceased logging of native forests and there is sustained pressure to extend this to all states (Burnett 2023). The basis of the arguments for a cessation of native forest logging in Tasmania is to protect biodiversity and carbon sequestration to help lessen the risks from climate change. Most of the published evidence presented in arguing for cessation of logging is based on carbon sequestration benefits (Mackey et al. 2022, Wilderness Society 2022). Evidence supporting these claims draws extensively on the Tasmanian and national greenhouse gas inventories (Commonwealth of Australia 2021, Renewables Climate and Future Industries Tasmania 2023).

The model used for greenhouse gas inventorying of the land use land use change and forestry sector (LULUCF) – FullCAM – uses the 3-PG model to predict forest growth (Landsberg and Waring 1997, Kesteven et al. 2004, Richards and Evans 2013). Forest growth is a fundamental property in calculating the amount of carbon sequestered by a forest (May et al. 2012). There are several climate variables used in the 3-PG model, but temperature, vapor pressure deficit (VPD) and soil water content are most relevant in the context of climate change. VPD and soil moisture content are much stronger modifiers of forest growth that temperature in 3-PG (Kesteven et al. 2004). This is the opposite of findings from eddy covariance measurements of productivity in the *E. obliqua* tall forest at Warra (Bennett et al. 2021, Wardlaw 2022).

The small influence of the temperature modifier in the 3-PG model means, growth of tall eucalypt forests in Tasmania predicted in FullCAM are likely to be over-estimated, and the size of the over-estimation will increase as the climate warms. Carbon sequestered by tall eucalypt forests in Tasmania will be less than the model predicts. If the temperature rise crosses a tipping point for these forests causing death of the current generation of eucalypts, the amount of carbon sequestered will drop sharply. This is because the eucalypt component dominates aboveground biomass of these forests (Moroni et al. 2017, Wardlaw 2021).

Analyses that conclude the protection of carbon-dense tall eucalypt forests is the safest option for addressing climate change (Mackey et al. 2022) do not account for the impact of the changed climate on future forest growth. Law et al. (2018) did conclude protection as the safest climate mitigation option in the carbon dense coniferous forests of the Pacific-Northwest USA. Their analysis was based on a prediction of higher growth rates in a future warmer climate. Their conclusions may have been very different if the analysis was based on lower forest growth rates in a warmer future climate as is suggested by the evidence for tall eucalypt forests in Tasmania.

A policy to end native forest logging in Tasmania using the argument that it would be the safest way to get climate change mitigation benefits from forests would be dangerous if it relied on existing carbon inventory analyses. Good policy must first require an analysis that takes account of the now known vulnerability of Tasmania's tall eucalypt forests to a warmer climate. Because of the vulnerability to a warming climate, good policy must also enable adaptation measures that will result in future tall eucalypt forests that are better suited to the new, warmer climate. On the best available knowledge, enhanced nature selection that relies on regeneration using locally sourced seed is the most promising adaptation measure. As this adaptation option is only feasible in production forests, a policy decision to end native forest logging would preclude this adaptation measure.

Conclusions

Tasmania's unique climate environment is associated with the very different responses to heatwaves measured in a Tasmanian tall eucalypt forest compared with similar temperate eucalypt forests on mainland Australia. A narrow annual temperature range, low moisture limitation, low winter radiation, but not low optimum temperature (for GPP), all contribute to the distinctive responses to heatwaves measured in Tasmanian tall eucalypt forest.

The distinctive responses to the climate environment determines enhanced natural selection to be the most promising management option to assist future tall eucalypt forests in Tasmania adapt to their new climate environment. Because enhanced natural selection is only feasible to do in forests managed for wood production, careful consideration needs to be given to ensure policy settings do not become an impediment to climate change adaptation.

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Appendix 1. Stomatal diffusive resistance - vapor pressure deficit relationship in regrowth *Eucalypts obliqua* forest at Hastings, southern Tasmania.

Methods

The study was done in a tall open forest of *Eucalyptus obliqua* near Hastings Caves State Reserve southern Tasmania (43°25’S. 146°53’E), which had regenerated naturally from a bushfire in 1908. The site is at the base of the southern slopes of Coal Hill on the edge of a wide floodplain of Lune River, which flows about 500m to the south. The soil at the site is described as a yellow podzol (Nicolls et al. 1982).

Sectional aluminium tree climbing ladders were fixed to the stem of one co-dominant *E. obliqua* with a healthy crown. The ladders provided access to the base of that tree’s crown at a height of approximately 25m. A lightweight aluminium pruning pole fitted with a butterfly net was used to obtain samples of shoots for measurement. The pruning pole allowed access to the crown of the ladder tree and eight adjacent *E. obliqua* trees. Shoot samples captured in the butterfly net were put into a weighted plastic bag and dropped to the ground for measurement. Measurements typically occurred within 5-10 minutes of sampling.

Measurement of stomatal diffusive resistance was done on a single, fully expanded leaf on the excised shoot. A LI-65 autoporometer fitted with a LI-20S diffusive resistance sensor (Licor, Lincoln, Nebraska, USA) were used to measure stomatal diffusive resistance. Measurements were corrected for leaf temperature according to manufacturer’s instructions. A Sholander pressure bomb (Model 3000 Plant Water Status Consul, Soil Moisture Equipment Corporation, Santa Barbara California) was used to measure shoot water potential. An aspirated psychrometer enclosed in a radiation shield was used to obtain wet and dry bulb temperatures at ground-level in the forest. A psychrometric chart was used to obtain relative humidity and saturation vapor pressure from the dry and wet bulb temperatures. Vapor pressure deficit (VPD) was calculated as the difference between saturation vapor pressure and the partial pressure of water vapour in the air as calculated from relative humidity.

Shoot sampling and measurement campaigns were done on four occasions: 14-15 Jan 1981, 15-16 Feb 1982, 19-20 Mar 1982, 25-26 Jan 1983. Each campaign consisted of an afternoon and a pre-dawn sampling of 5-8 of the sample trees. Measurements of stomatal diffusive resistance and VPD and shoot water potential from afternoon sampling visits were plotted to explore their relationship. Bureau of Meteorology records of temperature and rainfall from the Cape Bruny Lighthouse, 23km southeast of the study site, were extracted from the online data portal for four campaign days and compared with long-term averages to detect any significant anomalies.

Results

Rainfall during the four measurement campaigns was close to average for the two campaigns in 1982 and within one standard deviation of average for the January 1981 campaign (below average) and January 1983 campaign (above average). Mean daily temperature was close to average for the January 1981 and January 1983 campaigns, 1.5 standard below average for the March 1982 campaign and more than 3 standard deviations above average for the February 1982 campaign. The afternoon of the 15th February 1982 reached 39°C and is the hottest day on record for southern Tasmania. The very hot conditions on 15th February 1982 resulted in very high VPDs, >6 kPa, developing in the afternoon. Stomatal closure as evidenced by high diffusive resistance values, appears to be a threshold response when VPD exceeds 6 kPa (Figure A1). By contrast, stomatal closure occurred across a wide range of shoot water potentials: there was no evidence of stomatal closure showing a threshold response to shoot water potential (Figure A2).

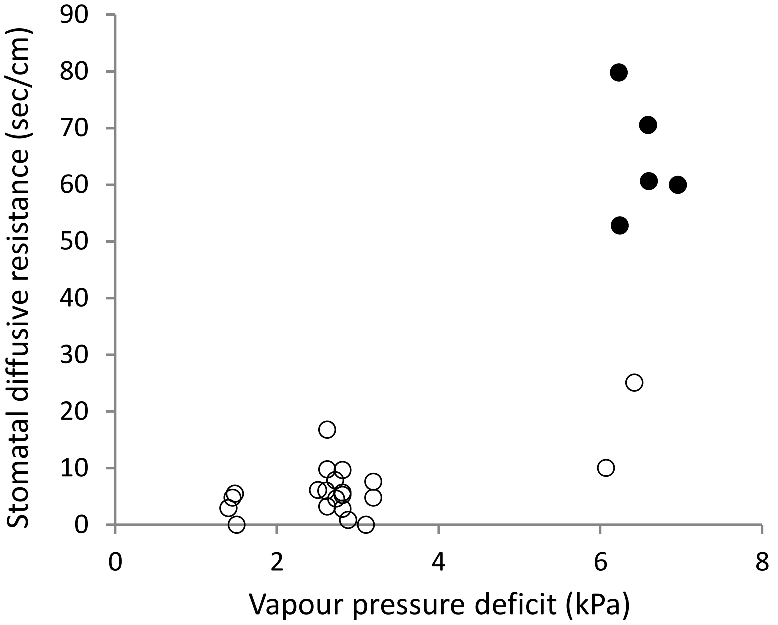

Figure A1. Plot of stomatal diffusive resistance and VPD of excised shoots from ca. 70 y.o. *Eucalyptus obliqua* at Hastings. All measurements were done during the afternoon period of four campaigns. Filled symbols indicate inferred stomatal closure.

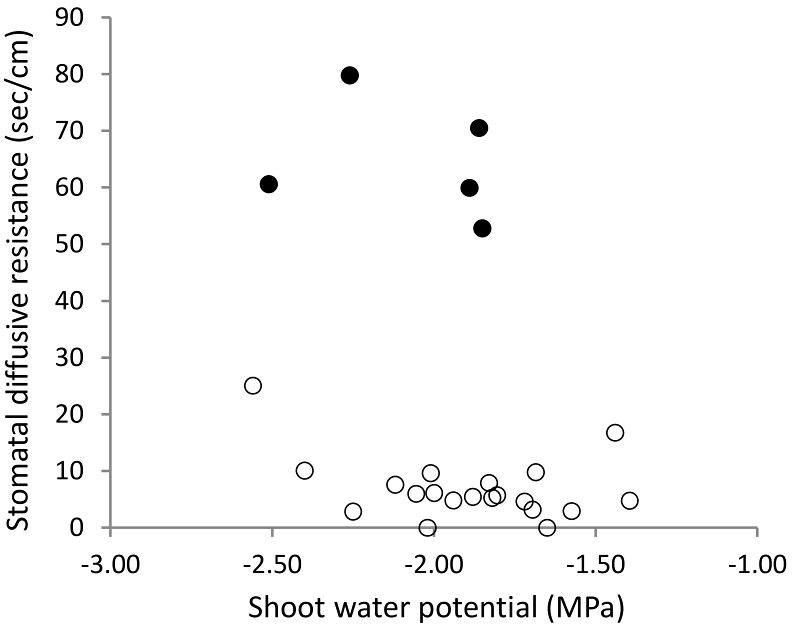

Figure A2. Plot of stomatal diffusive resistance and shoot water potential of excised shoots from ca. 70 y.o. *Eucalyptus obliqua* at Hastings. All measurements were done during the afternoon period of four campaigns. Filled symbols indicate inferred stomatal closure.