Giants Under Threat

The vulnerability of Tasmania's tall eucalypt forests to a warming climate.

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climatefutures

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Foreword

Eddy covariance flux towers have revolutionised our knowledge of ecosystem - atmosphere gas exchange in a multitude of ecosystems and especially complex forests. Stoy et al[49] catalogued over 1200 flux towers operating around the world that generate data contributing to a better understanding of ecosystem function, real time ecosystem response to extreme events and the capacity to accurately model at a broad scale vegetation – atmosphere interactions. Australia is fortunate to have an expanding number of flux towers through NCRIS-enabled TERN/OzFlux. Whilst the Australian network of flux sites is small by world standards, the ecosystems they operate in are globally unique and have generated new insights on energy, carbon and water budgets in natural ecosystems.

The Warra flux tower operated over a 9-year period from 2013. As such it had a number of unique features – initially operating in multiple use State forest and then the Tasmanian Wilderness World Heritage Area, contributing to a much broader in-depth ecological study as part of the Warra Long Term Ecological Research site that was established in 1998 and being at the latitudinal extreme of eucalypt forest in Australia but part of a latitudinal network of flux sites in ecosystems dominated by the species of the same genus. It has delivered significant new knowledge on the pattern and quantum of fluxes and the response of the tall eucalypt forest to temperatures exceeding the optima for growth of the key eucalypt species and why the response of these forests may differ from other eucalypt forests.

Demonstration of the temperature sensitivity of the magnificent, complex and dynamic tall eucalypt forests of Tasmania has implications for carbon storage and emissions, wood production and long-term forest composition and form. Atmospheric carbon dioxide levels continue to rise, average global temperatures edge upwards and the incidence of extreme events such as droughts and heatwaves are projected to increase. In the face of these trends, consideration turns to the resilience of the forests and how they might adapt and can management assist. The report deals with adaptation in depth, building on the flux studies and results from the Warra Long Term Ecological Research site. The latter is an important example of the value of long-term management driven research. Although the management focus at Warra has changed with the transfer from multiple use State forest to world heritage, the combined results can inform adaptive management for the future. There is still much to learn but this report sets out a way forward.

I would like congratulate Tim Wardlaw on his dedication and persistence in the development and scientific productivity of the Warra Long Term Ecological Research site since 1998, his championing of its ongoing value in the transition from multiple use State forest to world heritage and his initiative in establishing and maintaining the flux tower in the face of funding and infrastructure difficulties and natural disasters. Tim has made an enormous contribution to forest health in both native forests and plantations in Tasmania over several decades. This report- a science summary and a guide to policy makers and managers, is a further testament to the breadth of his achievements and the ongoing value of specialist forest health expertise.

Dr Glen Kile AM FTSE

Preface

In scientific research, there are critical pieces of work that surpass the mere advancement of knowledge and become conversant with contemporary issues and policy development. Dr Tim Wardlaw's research journey chronicled in this report exemplifies the pursuit of discovery intertwined with the imperative need to protect our biodiversity under a changing climate.

The Warra TERN SuperSite is Australia's longest running Long Term Ecological Research site and has also been one of the most scientifically productive over the past two decades. Scientific research conducted at Warra has underpinned real improvements in forest practices and an improved understanding of the tall forest biome and its response to disturbances. Dr Wardlaw's report, and the scientific research supporting it, presents strong evidence of the clear and present danger of climate change to this biome. In this respect it is, therefore, of critical importance not only to Tasmania, but nationally and internationally.

But the Warra SuperSite and the Southern Forests hosting it, sum to more than a scientific field site. Warra occupies a special place in the Tasmanian psyche. It is emblematic of the tensions, interconnections and natural disasters that are integral to living in the island state of Tasmania. These tensions and interconnections exist in the juxtaposition of contrasting and overlapping landscape elements: alpine environments with ancient conifer lineages, tall wet eucalypt forests, wild rivers, the globally renowned Tasmanian Wilderness World Heritage Area, and forest production zones. They are apparent in the multiple intersecting uses of the site: tourism and the spectacular Tahune airwalk; local recreational uses; timber production activities; conservation protests; beekeeping; scientific research; and many more.

In this respect then, the impacts of climate change are not simply those on the physical environment; they cut much deeper, and wider. This is why appropriate and timely responses can so often induce policy paralysis. But here, Dr Wardlaw provides carefully considered and deeply thoughtful recommendations for the site's future, presenting a transformative opportunity that would leverage existing physical and administrative infrastructure and partnerships to support a centre of global educational and scientific significance. Central to Dr Wardlaw's vision is the notion of knowledge exchange, where scientific insights resonate not only within academic circles but also inform policies and strategies ensuring that climate considerations are integrated into all facets of decision-making. In the context of Tasmania's *Climate Change Action Plan*, the recommendations presented here can help facilitate evidence-based decisions that empower policy development, particularly in relation to Tasmania's forests.

These recommendations therefore provide a platform on which apparently disparate players from different sectors can form strategic partnerships to harness collective resources to expand scientific excellence and take public forest education beyond the island state of Tasmania. The Warra TERN SuperSite has been pivotal in bringing us together to focus on the threat of climate change. Adopting Dr Wardlaw's recommendations can help achieve this. More than that, their adoption has the potential to offer both hope and knowledge for climate adaptation and understanding. They can help craft a uniquely Tasmanian perspective on understanding and dealing with the challenges of climate change that is relevant well beyond Tasmania.

Dr Kathleen Beyer and Dr Kathryn Allen, Climate Futures, University of Tasmania

Acronyms

AFWI	Australian Forest and Wood Innovations (formerly NIFPI)
DNRE Tas	Department of Natural Resources and Environment Tasmania
DCCEEW	Department of Climate Change, Energy, the Environment and Water
FEF	Forest Education Foundation
FPA	Forest Practices Authority
FullCAM	Full Carbon Accounting Model
LTER	Long Term Ecological Research
LULUCF	Land-use, land-use change, and forestry
NCRIS	National Collaborative Research Infrastructure Strategy
NIFPI	National Institute of Forest Products Innovation (now AFWI)
PFT	Private Forests Tasmania
PWS	Parks and Wildlife Service
ReCFIT	Renewables, Climate and Future Industries Tasmania
STTas	Sustainable Timber Tasmania
TFFPN	Tasmanian Forest and Forest Products Network
TERN	Terrestrial Ecosystem Research Network
TWWHA	Tasmanian Wilderness World Heritage Area
UNESCO	United Nations Education, Scientific and Cultural Organisation
UTas	University of Tasmania

Executive Summary

Recent studies have found the tall eucalypt forest at Warra, within the TWWHA, to be vulnerable to global warming. The forest there shows an unusually high sensitivity to temperature – as temperatures rise, the productivity of the forest declines strongly.

The vulnerability of the tall eucalypt forest in the TWWHA to warmer temperatures is the result of a unique response not previously seen in Australian forests. The forest shows a strong decline in productivity when neither moisture nor sunlight are limiting but temperature is above the relatively low optimum temperature for productivity of the forest. That unique response may be linked to Tasmania's tall eucalypt forests receiving abundant rainfall and being exposed to a narrow temperature range.

As warming continues, the current generation of tall eucalypt forests in the TWWHA will be increasingly maladapted to the climate. Their productivity will decline, which will reduce the amount of carbon they sequester and wood they produce. The forests will become a net emitter of CO_2 for increasing amounts of time. If the forests are a net emitter of CO_2 for too much of the time, they may cross a tipping point where they can no longer recover to sequester carbon. At the present rate of warming, the current generation of tall eucalypt forests in the TWWHA may start to experience dangerous levels of warming that trigger mass tree deaths (tipping points) within three decades.

The direct effect of a warming climate on the health and productivity of tall eucalypt forests is not currently considered as a threat from climate change. This needs to change. If the high temperature sensitivity observed at Warra reflects tall eucalypt forests elsewhere in Tasmania there will be major implications.

Implications for emissions reduction and climate change

- Current methods used to calculate forest growth are likely to produce large overestimates for Tasmania's tall eucalypt forests, and the amount of the overestimation will continue to increase as the climate warms.
- The status of the TWWHA as UNESCO's number one ranked property in terms of the amount of carbon sequestered annually by the forest it contains will be in jeopardy.
- The large carbon uptake by the tall eucalypt forests will be greatly reduced. Consequently, the capacity of the LULUCF sector to offset the emissions of other sectors will be lower and may jeopardise Tasmania's net zero emission status.
- Mass tree deaths in tall eucalypt forests from temperature tipping points being crossed, will, without restoration, result in a large and permanent reduction in the amount of carbon sequestered.

Implications for conservation of natural values

- The Outstanding Universal Value that the tall eucalypt forests provide to the listing of the TWWHA on the Register of World Heritage Areas will be threatened if mass tree deaths occur and no restoration is done.
- The high proportion of the biodiversity that is dependent on habitats provided by the eucalypts in tall eucalypt forests will decline due to a reduction in the amount and quality of those habitats.

Implications for wood production

- The lower growth rates of tall eucalypt forests in the Permanent Timber Production Zone will have a disproportionate impact on future sawlog supply. A large opportunity cost will be incurred in the second half of this century, when demand for wood products is forecast to be high.
- Predictions of higher productivity of Tasmanian eucalypt plantations in a warmer climate assumes that productivity increases with temperature. This needs to be verified by observations.

Effective Adaptation Measures

Implementing effective adaptation measures to increase the resilience of future generations of tall eucalypt forests will have a long lead time. There is currently a window of opportunity to verify the most prospective way to increase the climate resilience of future generations of tall eucalypt forests; to ensure the right policy settings are in place; and there is a social licence to implement adaptation responses. An effective adaptation response has four elements.

Understanding why the tall eucalypt forests are so sensitive to warming temperatures

Better knowledge and understanding will strengthen capacity to predict future outcomes and to guide the selection of traits important for increasing resilience to a warmer climate.

Verifying that future forests can be made more resilient to a future warmer climate

Future forests that are more resilient to a warmer climate will remain productive at higher temperatures and be more likely to avoid temperature tipping points. *In situ* enhanced natural selection has been identified as the most prospective approach, but this needs to be verified. *In situ* enhanced natural selection is only practical to do in forests managed for wood production.

New knowledge and understanding informs policy settings

Policy decisions strengthened by better knowledge and understanding about the impact of higher temperatures on forest productivity and of the capacity to reduce those impacts through having more climate resilient future forests.

Effectively communicate the science, the management, and the policy to get community involvement in, and support for, implementing adaptation responses

Strengthen existing linkages between Warra, Tahune Adventures and Forest Education Foundation using real time data from Warra SuperSite to communicate and educate diverse audiences on the effect a warming climate is having on tall eucalypt forests. These strengthened linkages also provide opportunities to engage with the public on how we can make forests more resilient to a warmer climate and what we might do if tall eucalypt forests in reserves suffer mass death events. The status of the TWWHA as UNESCO's number one-ranked property for forest carbon sequestration could be a platform to develop partnerships for communicating and educating about climate change and carbon sequestration by tall eucalypt forests in the TWWHA.

Ongoing operation of the Warra SuperSite underpins many of the actions needed to monitor the impact of progressively warming temperatures on health and productivity of the tall eucalypt forests and in the development of adaptation measures. A next generation of expertise in operational forest health management will be needed to help advance those adaptation measures and to guide their implementation.

The proposed adaptation responses provide Tasmania with an opportunity to reset the debate on how its forests are managed. Production forestry, nature conservation and tourism will need to work together if we are to be successful in creating the climate-resilience needed for tall eucalypt forests to persist in a future warmer climate.

Photograph by Simon Gregory

List of recommendations

Recommendation 1

The risk that a hotter and drier climate will have direct adverse impacts on the health and productivity of Tasmania's tall eucalypt forests be recognised and included in the Statewide Risk Assessment being undertaken as part of Tasmania's Climate Action Plan 2023-25.

Recommendation 2

Extend forest productivity monitoring done at Warra to tall eucalypt forests elsewhere in Tasmania using a low-cost dendrometer network and satellite remote sensing.

Recommendation 3

Support the ongoing long term monitoring in the tall eucalypt forest such as has been the case at the Warra SuperSite. Promote the use of monitoring data to support monitoring obligations and the management of the tall eucalypt forests in the TWWHA.

Recommendation 4

Review the formulation of the 3PG module of FullCAM to determine if the growth decline with warming temperatures observed in tall eucalypt forests at Warra (and more broadly in Tasmania) is accurately predicted. If necessary, revise the structure of the temperature modifier in 3PG to better reflect the observed growth response to temperature.

Recommendation 5

Calculate the impact on future sustainable yield from public tall eucalypt forests due to changes in productivity as the result of predicted warmer temperatures.

Recommendation 6

Determine the way productivity responds to temperature in Tasmanian *E. nitens* plantations to establish whether they show a similar sensitivity to a warming climate as tall eucalypt forests.

Recommendation 7

Undertake a synthesis of findings from biodiversity studies done in tall eucalypt forests to identify taxa associated with habitats developing in eucalypt trees and logs.

Recommendation 8

Use natural capital accounting procedures to monetise the consequences to carbon sequestration, wood production and biodiversity arising from the vulnerability of Tasmania's tall eucalypt forests to a warmer climate.

Recommendation 9

Develop and conduct experiments to reveal and prove the mechanisms causing the unique responses to environmental change shown by the tall eucalypt forests at Warra and Tasmania more generally.

Recommendation 10

Obtain evidence that enhanced natural selection is providing meaningful, and measurable, gains in resilience to warmer temperatures within relevant timeframes.

Recommendation 11

Policy decisions on the optimum management of public tall eucalypt forest in Tasmania for sustaining multiple values takes into account: (i) the sensitivity of the current generation of tall eucalypt forests to warming temperatures; and (ii) the capability for introducing greater resilience to a warmer climate in future generations of tall eucalypt forests through enhanced natural selection.

Recommendation 12

Develop a forest restoration policy and accompanying procedures to allow timely decisions to be made on whether to, or not, restore a new generation of canopy-forming eucalypts after mass mortality events in reserves.

Recommendation 13

Develop opportunities for Tahune Adventures and Forest Education Foundation to use data and real-time measurements from Warra SuperSite to communicate and educate on the impact of, and responses to, a warming climate in Tasmania's tall eucalypt forests.

Recommendation 14

Seek a partnership with UNESCO to collaborate in showcasing the monitoring being done a Warra within the TWWHA and how that monitoring is being used to inform about impacts to tall eucalypt forests and guide the development of response actions.

Recommendation 15

Leverage the value of data from Warra SuperSite by packaging projects that use Warra data to address managing climate change risks to Tasmania's tall eucalypt forests.

Recommendation 16

Develop a model to fund, rebuild and sustain specialist expertise in operational forest health management in Tasmania.

Flowers of stringybark (*Eucalyptus obliqua*), roadside tree, Glenlusk.

Photo by Tim Wardlaw

Photograph by Simon Gregory

Tasmania's tall eucalypt forests

Tasmania's tall eucalypt forests are dominated by one or two of three Eucalyptus species – *E. obliqua*, *E. regnans* and *E. delegatensis*. These three species form the tall, emergent canopy layer above a mid-layer of trees and a ground layer of ferns and sedges[1]. The mid layer of understorey trees is one of three types:

- rainforest species, such as myrtle (*Nothofagus cunninghamii*) and sassafras (*Atherosperma moscahtum*);
- broad-leaf, wet sclerophyll species such as blackwood (*Acacia melanoxylon*), dogwood (*Pomaderris apetala*) and musk (*Olearia argophylla*);
- swamp-loving species such as tea tree (*Leptospermum* species) and paper barks (*Melaleuca* species).

Tall eucalypt forests occur in high rainfall areas of the state. A continuous band of tall eucalypt forests extends from the north-west corner to the south-east corner of the state. The other concentration of tall eucalypt forests occurs in the north-east corner of the state[2].

Tasmania is Australia's most forested state, with forests occupying nearly 50% of the land area. Tall eucalypt forests occupy 802,000 (24%) of the forest area, with most (86%) occurring on public land[3]. Of the tall eucalypt forests on public land, more than 60% (424,000 ha) are in formal or informal reserves. The remaining 269,000 ha of tall eucalypt forest on public land are in the Permanent Timber Production Zone that is available for timber harvesting.

Tasmania's tall eucalypt forests are among the world's tallest forests and contain the world's tallest flowering plant[4]. At maturity they amass greater quantities of biomass than any other forest ecosystem[5]. Also, over their life, these forests accumulate biomass faster than any natural forest ecosystem[4]. Tasmania's tall eucalypt forests are highly valued culturally, environmentally and economically because of these superlatives:

- The tall eucalypt forests within the Tasmanian Wilderness World Heritage Area (TWWHA) contribute to the Outstanding Universal Values recognised in the listing of the TWWHA on UNESCO's Register of World Heritage properties.
- The TWWHA is recognised as UNESCO's number one World Heritage property in terms of the amount of carbon sequestered annually by its forests[6].
- Carbon sequestered by the forests, particularly the tall eucalypt forests, has allowed Tasmania to claim net zero emission well before any other Australian jurisdiction[7].
- These forests have also provided most of the high-quality sawlogs supplying Tasmania's sawmilling industry for more than a century.

Understanding the threats that negatively impact those values is important. This includes new and emerging threats that are a consequence of climate change.

Threat to Tasmania's tall eucalypt forests from climate change

Changes to the frequency and intensity of bushfires in Tasmania's tall eucalypt forests are the main threats usually considered in the context of climate change[8]. Threats posed by changes in climate that act directly on the health and productivity of tall eucalypt forests are generally not considered. One reason for this is that Tasmania's tall eucalypt forests grow in a very moist, but cool, environment. There is a perception, in some quarters, that these forests are well buffered from climate change and their productivity may even increase from warming at the levels predicted in climate change models[9]. This dogma is now being challenged.

Direct measurement of tree growth in permanent forest inventory plots located in temperate, moist environments of Australia have found that rates of tree diameter growth peak at relatively low temperatures[10]. Direct measurement of forest biomass in tall eucalypt forests within an Australian network of permanent, 1-ha forest plots have similarly found the highest biomass forests tend to occur in the coolest environments[11]. Tasmania's tall eucalypt forests, it seems, are well adapted to a cool, moist environment.

> *Rather than a cool climate limiting the productivity of Tasmania's tall eucalypt forests, there is mounting evidence that the high productivity and biomass of these forests is because of the cool climate they have experienced historically.*

In March 2013 an 80m tall, instrumented flux tower in *Eucalyptus obliqua* tall forest at Warra, within the TWWHA was commissioned as part of Australia's national capability to monitor its terrestrial ecosystems – the NCRIS-enabled Terrestrial Ecosystem Research Network – TERN (www.tern.org.au). The flux tower at Warra provides an opportunity to monitor, in real time, how the forest is responding to weather events. Together with standard weather measurements, instruments on the tower measure the rates at which carbon dioxide, water and energy move between the forest and the atmosphere. Among other things, these measurements can show how changes in weather conditions and future climate change are affecting the capacity of the forest to remove carbon dioxide from the atmosphere and convert it into biomass through photosynthesis.

Photograph by Simon Gregory

Measurements from the Warra flux tower have confirmed that the forest there has an optimum temperature for peak productivity, which is low relative to most other forests in Australia[12]. We find that the optimum temperature for productivity of a forest reflects the average temperatures experienced by the forest. As well as having a low optimum temperature, the rate of carbon uptake by the forest at Warra is much more sensitive to departures in temperature away from that optimum compared with other forests in Australia's temperate regions[12]. The productivity of the forest at Warra drops sharply when temperatures rise above the optimum.

Measurements of growth in forest inventory plots, and of carbon fluxes by instrumented flux towers, are telling the same story – global warming is likely to reduce the rate that Tasmania's tall eucalypt forests sequester carbon.

Heatwaves represent warming temperatures at their extreme. Tasmania experienced a record heatwave event in November 2017. Measurements from the Warra flux tower during that heatwave showed the forest rapidly switched from being a net carbon sink, removing CO_2 from the atmosphere, to become a net carbon source, releasing CO_2 into the atmosphere[13]. The tall eucalypt forest at Warra showed a much stronger decline in productivity during a heatwave event compared with tall eucalypt forests elsewhere (Victoria and southern New South Wales). This stronger heatwave response by the Tasmanian forest is a reflection that its productivity shows a much higher sensitivity to temperatures that are above the optimum for productivity than the tall eucalypt forests elsewhere in southeastern Australia.

The 2017 Tasmanian heatwave lasted three weeks and temperatures were above the optimum during the middle hours of the day for much of the period. During the middle part of the day when temperatures were above optimum, CO_2 uptake by the forest (through photosynthesis) was strongly reduced, and CO_2 loss from the forest (through respiration) was strongly enhanced①. It was this reduction in photosynthesis and increase in respiration at above-optimal temperatures that caused the forest to switch from being a carbon sink to become a carbon source.

The pattern of responses to the heatwave measured in tall eucalypt forest at Warra matches those found in a recent global analysis of vegetated ecosystems -there is a general pattern of responses when temperatures exceed the ecosystem optimum for photosynthesis[14]. That analysis raised the alert that, because of climate change, "new normal" temperatures in many of the world's vegetated ecosystems will exceed their optimum for productivity (Box 1). When this happens, those ecosystems will have passed a temperature tipping point and no longer provide a carbon sink. Based on current climate projections, that tipping point may be crossed within the next 2-3 decades for many ecosystems. If that happens, the land carbon sink would shrink by half. The ecosystems most at-risk (of crossing a temperature tipping point) were concentrated in tropics.

Tasmania is a long way from the tropics, but, like tropical forests, Tasmania's tall eucalypt forests have a heightened sensitivity to above-optimum temperatures[12] and a heightened vulnerability to drought[15]. Tasmania is also experiencing multi-decadal trends of both warming temperatures and reducing rainfall[16]. In combination, the warming and drying climate and the temperature / drought sensitivities increase the risk of adverse impacts to the health of Tasmania's tall eucalypt forests. We are already seeing large reductions in forest productivity following heatwaves[17]. We do not yet understand what will happen when the temperature tipping point is crossed, but mass tree mortality from carbon starvation② is a possibility. We can also expect an increased likelihood of mass tree mortality events that are caused by drought conditions and heatwaves coinciding[18]. One such event occurred in eastern Tasmania, which was experiencing drought when the 2017 heatwave occurred. The tall eucalypt forest at Evercreech Forest Reserve suffered extensive crown dieback and mortality from that event.

We need to plan for the possibility that many of Tasmania's current generation of tall eucalypt forests will cross a temperature tipping point within the next 3 decades. When this happens, impacts from declines in forest growth will be amplified by the impact of mass mortality events.

Large reductions in productivity and mass tree mortality resulting from a warming climate would each be consequential on the ecosystem service values provided by Tasmania's tall eucalypt forests. We need to give much stronger consideration to the direct threat from climate change to the health and productivity of Tasmania's tall eucalypt forests.

Recommendation 1

The risk that a hotter and drier climate will have direct adverse impacts on the health and productivity of Tasmania's tall eucalypt forests be recognised and included in the Statewide Risk Assessment being undertaken as part of Tasmania's Climate Action Plan 2023-25.

Box 1

Changes in productivity of the forest with temperature at Warra

The measurements of carbon exchanges made by the instruments on the flux tower at Warra can be separated into two processes – CO_2 from the atmosphere taken into the leaves and converted into sugars through photosynthesis, so-called gross primary productivity (GPP), and CO_2 released from the forest into the atmosphere through respiration, so called ecosystem respiration (ER). The net difference between GPP and ER is the net Carbon (C) sink strength. The rates that CO_2 moves into and out of the forest through photosynthesis (GPP) and respiration (ER), respectively, varies with temperature. The graph in Figure 1 shows how GPP, ER, and C sink strength of the tall eucalypt forest at Warra varies with temperature.

The relationship between GPP and temperature is a parabola ("upside down U"). At the top of the parabola, GPP reaches its maximum and the temperature at that point represents the optimum temperature for GPP (T_{OPT}). For the forest at Warra, the optimum temperature for GPP is 17°C. Across the range of temperatures experienced at Warra, ER increases exponentially as temperature increases. The C sink of the tall eucalypt forest at Warra shows a parabolic relationship with temperature like that of GPP. But, because of effect of ER, the C sink reaches its maximum at a temperature of 13°C, well below T_{OPT} for GPP, and declines more rapidly once temperatures exceed the C sink maximum. The maximum C sink is also below the current daily mean temperature for the summer months at Warra, which is shown as the vertical dashed line in the middle of the pink-shaded average daily temperature range for the summer months at Warra (Figure 1).

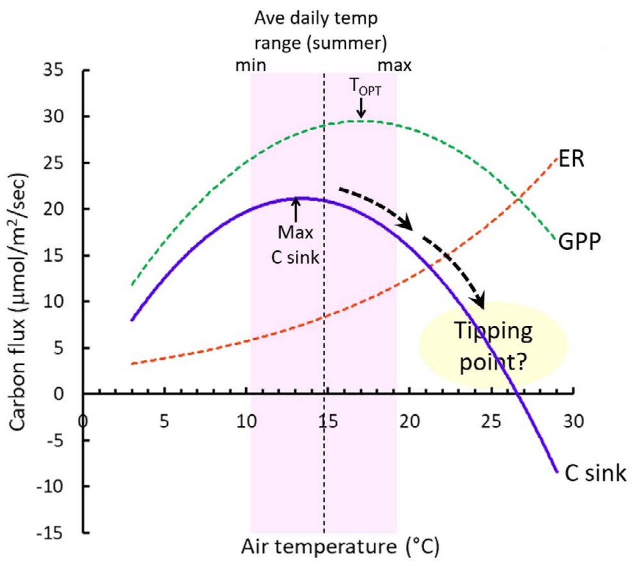


Figure 1. Relationships between the rates of carbon exchange (flux) and air temperature of the Eucalyptus obliqua tall forest at the Warra SuperSite. The carbon exchanges have been separated into gross primary productivity (GPP) and ecosystem respiration (ER) and the strength of the C sink - the difference between GPP and ER. Explanation of how the data shown in Figure 1 were obtained is given in Appendix 1.1.

Because the current daily mean summer temperature is already higher than the C sink maximum, the C sink of the forest at Warra will weaken as temperatures continue to rise as the result of global warming. The weakening of the C sink will be much stronger during heatwaves when temperatures are above T_{OPT}. This is because when the temperature is above T_{OPT}, GPP is declining while ER is increasing – changes in GPP are amplified by changes in ER.

Currently, the C sink can recover when cooler temperatures return after warm spells. Will the C sink be less able to recover after warm spells as those warm spells occur more regularly? Will a tipping point be reached when the forest C sink cannot recover, and if so, when? We do not yet know the answers to these questions. Continued monitoring of the carbon exchanges in the forest at Warra will help to answer these questions.

Consequences of adverse impacts to the health and productivity of tall eucalypt forests

Based on the analysis of an extensive network of forest inventory plots[10], declining rates of tree growth as temperature increases in tall eucalypt forests is likely a general effect. The stronger effect of heatwaves on carbon uptake in tall eucalypt forests, has only been measured at one site (Warra). It is this stronger heatwave response that will likely be most consequential to health and productivity of Tasmania's tall eucalypt forests. The heatwave response measured at Warra would need to be replicated at other sites before concluding the response is general for all tall eucalypt forests in Tasmania. Replicating the monitoring infrastructure installed on the flux tower at Warra in tall eucalypt forests elsewhere in Tasmania would be very expensive. Continuous measurement of tree stem growth made using dendrometers (dendrometry) and of temperature can provide comparable information as that provided by flux measurements from instrumented towers[19].

Remotely sensed measurements from satellites are also able to provide information that agrees with those provided by flux measurements from instrumented towers[20]. Both techniques (dendrometry and satellite remote sensing) would require calibration with flux measurements made at Warra to help interpret dendrometer and remotely sensed measurements made in tall eucalypt forests elsewhere.

Remotely sensed measurements have the potential added benefit of providing full coverage of all tall eucalypt forests at regular intervals. Regular, full coverage measurements would be particularly useful for carbon accounting and would fit within the FullCAM model framework currently used to produce Australia's carbon accounts for the forest sector. New sensor technology that measures sun-induced fluorescence (SIF) may be particularly useful for monitoring changes in the productivity of Tasmania's tall eucalypt forests through remote sensing. This is because SIF can detect changes in productivity associated with the suppression of photosynthesis[21]. Suppression of photosynthesis at above-optimum temperatures was measured at Warra during the 2017 heatwave. A new SIF-measuring satellite - FLEX - is planned for launch by the European Space Agency in 2025. This satellite will have much higher spatial resolution (800 metres) than previous satellites measuring SIF. Warra LTER site would be ideal to host a FLEX SIF sensor because the forest there shows a contrasting response of GPP to temperature compared with other forest sites in Australia. Warra would be an ideal second site to host a FLEX SIF sensor because the forests at Warra and Tumbarumba show contrasting responses in their GPP to temperature.

Recommendation 2

Extend forest productivity monitoring done at Warra to tall eucalypt forests elsewhere in Tasmania using a low-cost dendrometer network and satellite remote sensing.

Band dendrometer monitoring the growth of a stringybark (*Eucalyptus obliqua*) in the Core 1-ha plot of the Warra SuperSite.

Photo by Tim Wardlaw

Tall eucalypt forest landscape in the Tasmanian Wilderness World Heritage Area, looking south from Warra flux tower.

Photo by Michael Brown (ComStar Systems)

Recommendation 3

Support the ongoing operation of the flux tower and associated permanent 1-ha plot in the tall eucalypt forest at the Warra SuperSite. Promote the use of monitoring data to support monitoring obligations and the management of the tall eucalypt forests in the TWWHA.

World Heritage values

The distinctive features of tall eucalypt forests that contribute to their international significance – their exceptional growth rates and phenomenal height - will likely decline as the climate warms. That decline is likely to be most strongly felt in actively growing forests that have not reached their maximum biomass. There is also evidence that the adverse impacts of warming temperatures will be more strongly felt by the larger trees[22].

> *Tall eucalypt forests are of international significance as they provide the world's best examples of distinctive evolutionary features .... which includes exceptional growth rates, flammability, and phenomenal height.*[3]

Mass mortality events, if they occur in the absence of fire, will likely hasten the transition of tall eucalypt forest to rainforest or scrub. This would greatly diminish the value of those parts of the TWWHA dominated by tall eucalypt forests.

Fire, particularly if it kills sufficient canopy eucalypts to allow regenerating eucalypt seedlings to survive, may provide some benefit to the climate resilience of the ecosystem. Adaptation through natural selection is the most likely way that resilience to a warmer climate will develop. Regeneration events are needed to drive natural selection. Natural disturbance from severe fire events in Tasmania's tall eucalypt forests are rare, even after factoring climate change[23]. Fires are unlikely to drive natural selection at the pace needed for adaptation to a rapidly warming climate because of this.

Mass mortality events pose the greatest risk to the values provided by the tall eucalypt forests in the TWWHA. Our understanding of a potential temperature tipping point for these forests needs to be refined and used to inform monitoring and management. Ongoing monitoring of the *E. obliqua* tall forest at the Warra SuperSite will be critical as the climate continues to warm and temperatures move towards a possible tipping point for the forest.

As a State Party to the World Heritage Convention, Australia is obligated to report periodically to the World Heritage Committee on the state of conservation and management of the TWWHA[24]. Ongoing monitoring of the tall eucalypt forest at Warra within the TWWHA contributes to several of the specified purposes of the periodic reporting, including: (i) whether World Heritage values are being maintained over time; (ii) report on changing circumstances and state of conservation of the property. The Natural Values Climate Change Adaptation Strategy for the TWWHA for 2021-31 explicitly states the ongoing operation of Warra long-term ecological research site was a priority[25].

Carbon sequestration

Tall eucalypt forests make a disproportionate contribution to carbon sequestration (carbon stores and growth) in the land-use, land-use change, and forestry sector (LULUCF) of Tasmania's greenhouse gas inventory[26]. Growth rates are a key driver of the amount of carbon sequestered by Tasmania's tall eucalypt forests[27]. Findings from both inventory and flux tower measurements, indicate that the growth rates of these forests are likely to decline, possibly sharply, as the climate warms. By mid-century, at the current rates of warming, carbon uptake by tall eucalypt forests could decline by 22-50% compared with the previous forest generation④. If the greater likelihood of mass mortality events in a warmer and drier future climate is realised, the impact on carbon sequestration will be even higher.

The FullCAM model is used calculate net greenhouse gas emissions from LULUCF. Forest growth is predicted by a module within FullCAM based on the 3PG forest growth model. Forest growth is relatively insensitive to fluctuations in temperature in the current formulation of the 3PG module[28] and is thus likely to over-estimate growth when temperatures are above optimum for growth.

"Predictions of growth in Tasmanian tall eucalypt forests made using FullCAM will be over-estimated when above-optimal temperatures occur during the spring-summer growing season. The amount that forest growth is over-estimated will increase as warming continues."

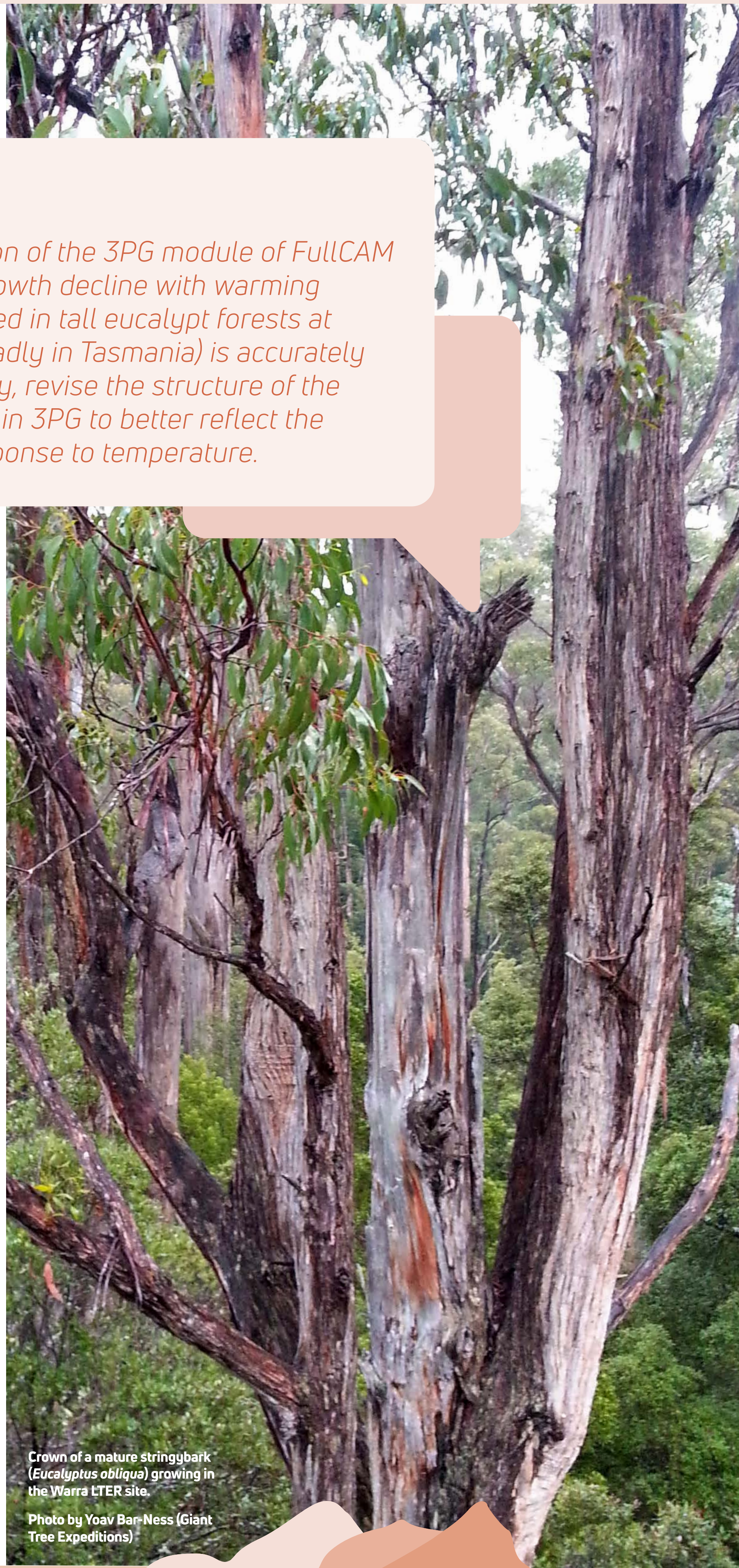
Ideally, FullCAM should be calibrated to better represent the sensitivity to temperature shown by Tasmanian tall eucalypt forests, but further work would be needed preparatory to calibration. Currently, the growth response to temperature in Tasmania's tall eucalypt forests is modelled using data from just one site – the Warra SuperSite.

Growth - temperature relationships need to be developed for more Tasmanian tall eucalypt forest sites. This will allow variation in the growth – temperature relationships in tall eucalypt forests to be represented in any model. A dendrometer network (Recommendation 2) would do this if dendrometry was the method used. Any project to calibrate the temperature modifier in 3PG to better represent tall eucalypt forests in Tasmania should be done in collaboration with the Department of Climate Change, Energy, Environment and Water (DCCEEW) as they are responsible for the national greenhouse gas inventory.

Mass mortality events occurring in the absence of fire would likely hasten the transition of tall eucalypt forests to shorter stature rainforest or scrub. Where this transition has occurred, there is a large decrease in carbon carrying capacity of the resultant non-eucalypt ecosystem[29]. FullCAM has the capability to model changes to carbon stocks from such transitions provided the areal extent of mass mortality has been mapped. But mass mortality events are still rare and of limited extent in Tasmania's tall eucalypt forests. Currently, it is probably a low priority that protocols for representing mass mortality events in FullCAM are developed.

Recommendation 4

Review the formulation of the 3PG module of FullCAM to determine if the growth decline with warming temperatures observed in tall eucalypt forests at Warra (and more broadly in Tasmania) is accurately predicted. If necessary, revise the structure of the temperature modifier in 3PG to better reflect the observed growth response to temperature.



Crown of a mature stringybark (*Eucalyptus obliqua*) growing in the Warra LTER site.

Photo by Yoav Bar-Ness (Giant Tree Expeditions)

Wood production

Like carbon sequestration, growth rates are an important driver of wood production in tall eucalypt forests. At the current rates of warming, by mid-century, tall eucalypt forests supplying future sawlogs could take 22-50% longer to reach a target yield, compared with the previous forest generation[4]. The additional sawlog supply provided by plantations may offset any warming-induced reduction in future yields from native forest.

The capacity of plantations to offset reductions in future yields from tall eucalypt forests depends on the productivity of plantations being resilient to the projected changes in climate. Past modelling has predicted Tasmanian pine and eucalypt plantations will be more productive in projected future climates[30]. But there is a lack of empirical evidence, particularly from older Tasmanian plantations, to be confident of these predictions of their climate resilience. *Eucalyptus nitens* plantations are of particular concern in this regard. This is because *E. nitens* maintains high productivity at the expense of controlling water loss just like *E. obliqua* and *E. regnans* [31] – the dominant species in Tasmania's lowland tall eucalypt forest. Obtaining empirical evidence of the predicted climate change resilience of Tasmanian plantations, particularly older plantations, should be a high priority. Investing in the installation of a carbon flux tower within a *E. nitens* plantation may be justified given the significance of the knowledge gap.

Recommendation 5

Calculate the impact on future sustainable yield from public tall eucalypt forests due to changes in productivity as the result of predicted warmer temperatures.

Thinned *E. nitens* plantation
Photo by Tim Wardlaw

Recommendation 6

Determine the response of productivity to temperature in Tasmanian E. nitens *plantations to establish whether they show a similar sensitivity to a warming climate as tall eucalypt forests.*

Despite plantation offsets, a warming-induced reduction in future sawlog yields from native forests of 22-50% would represent a considerable opportunity cost in the second half of this century. That opportunity cost is only likely to increase given an expected quadrupling in the demand for wood products by mid-century[5]. A comprehensive analysis of the opportunity costs resulting from a decline in future growth rates of Tasmania's tall eucalypt forests should inform decisions on investments to develop adaptation options.

The impact of climate change on wood production from tall eucalypt forests will be much greater if there is an upsurge in mass mortality events. Trees rapidly become unsuitable as sawlogs after death, so increases in mortality would have the greatest impact on sawlog supply. Such impacts may be reduced if there is flexibility to rapidly redirect harvesting to areas with recently dead and dying trees containing high volumes of sawlogs. Given the greater likelihood of mass mortality events in a warmer and drier future climate, the eventuality of increases in mass mortality events should be planned for.

Biodiversity

The eucalypts that form the canopy of Tasmania's tall eucalypt forests are the keystone species for this ecosystem – they provide the habitat for many of the species within the forests.

- Hollow-dwelling animals, mostly birds, depend on the hollows that develop in mature eucalypts.
- A high diversity of fungi are dependent on eucalypts to host mycorrhizal associations.
- A high diversity of fungi and insects, particularly beetles, are dependent on dead-wood habitat produced in great abundance by eucalypts as forests age.
- A high diversity of lichens and bryophytes depend on the light environment developing on the stems and branches of living eucalypts.

Lower productivity would likely increase the time needed for mature tree structures, such as hollows, to develop. Lower productivity, coupled with more frequent fires would likely reduce the amount, size and longevity of eucalypt logs that provide most of the dead wood habitat. Mass mortality events would reduce habitat for mycorrhizal fungi. While mass mortality events would provide an initial large pulse of dead wood, dead-wood habitats would quickly disappear unless a new generation of eucalypts regenerates after the mortality event.

Many detailed studies of the biodiversity associated with tall eucalypt forests have been done in the Warra Long Term Ecological Research site and surrounds. A synthesis of that knowledge would strengthen predictions of the effect that a warming climate would have on specific habitats developing in eucalypt trees and logs.

Recommendation 7

Undertake a synthesis of findings from biodiversity studies done in tall eucalypt forests to identify taxa associated with habitats developing in eucalypt trees and logs.

Recommendation 8

Use natural capital accounting procedures to monetise the consequences to carbon sequestration, wood production and biodiversity arising from the vulnerability of Tasmania's tall eucalypt forests to a warmer climate.

Natural capital

Natural capital accounting and reporting is rapidly gaining traction as a way for organisations to bring environmental assets into their business decision making[32]. Wood production for industry, provision of habitat for biodiversity and carbon sequestration each contribute materially to natural capital. In their latest natural capital report, Forico calculated a monetary value of $5.8B that these three components made to natural capital of the non-plantation component of the estate they manage. Carbon sequestration contributed the dominant (85%) proportion of that value[33]. Translating that valuation to Tasmania's public tall eucalypt suggests the value of carbon sequestration alone would be in excess of $20B.

The consequences of the vulnerability of Tasmania's tall eucalypt forests to a warming climate is encapsulated in Recommendations 3-6. The use of natural capital accounting[34] to monetise these consequences will provide a strong basis for:

- decision-making on the appropriate level of investment to manage the risks associated with the vulnerability of tall eucalypt forests to a warming climate;
- capitalise on future market opportunities to generate value from interventions that reduce the risk of serious adverse impacts;
- getting social licence for interventions that reduce risk of serious adverse impacts.


Darkling Beetle (*Coripera deplanata*), a common inhabitant of logs in tall eucalypt forests.

Photo by Dr Simon Grove (Tasmanian Museum and Art Gallery)

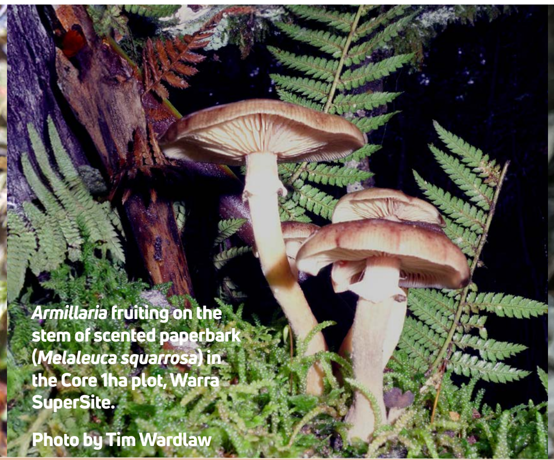

Armillaria fruiting on the stem of scented paperbark (*Melaleuca squarrosa*) in the Core 1ha plot, Warra SuperSite.

Photo by Tim Wardlaw


Morel (*Morchella elata*) fruiting after 2019 bushfire, Core 1-ha Plot, Warra SuperSite.

Photo by Alison Phillips (Sustainable Timber Tasmania)


Pink robin (*Petroica rodinogaster*) a common inhabitant of cool temperate forests in southeastern Australia.

Photo by Dr Simon Grove (Tasmanian Museum and Art Gallery)


Filmy fern (*Hymenophyllum sp.*) growing on the stem of a manfern (*Dicksonia antarctica*), Core 1-ha Plot, Warra SuperSite.

Photo by Tim Wardlaw

Leaves of stringybark (*Eucalyptus obliqua*) regeneration at Tahune Airwalk.

Photo by Tim Wardlaw

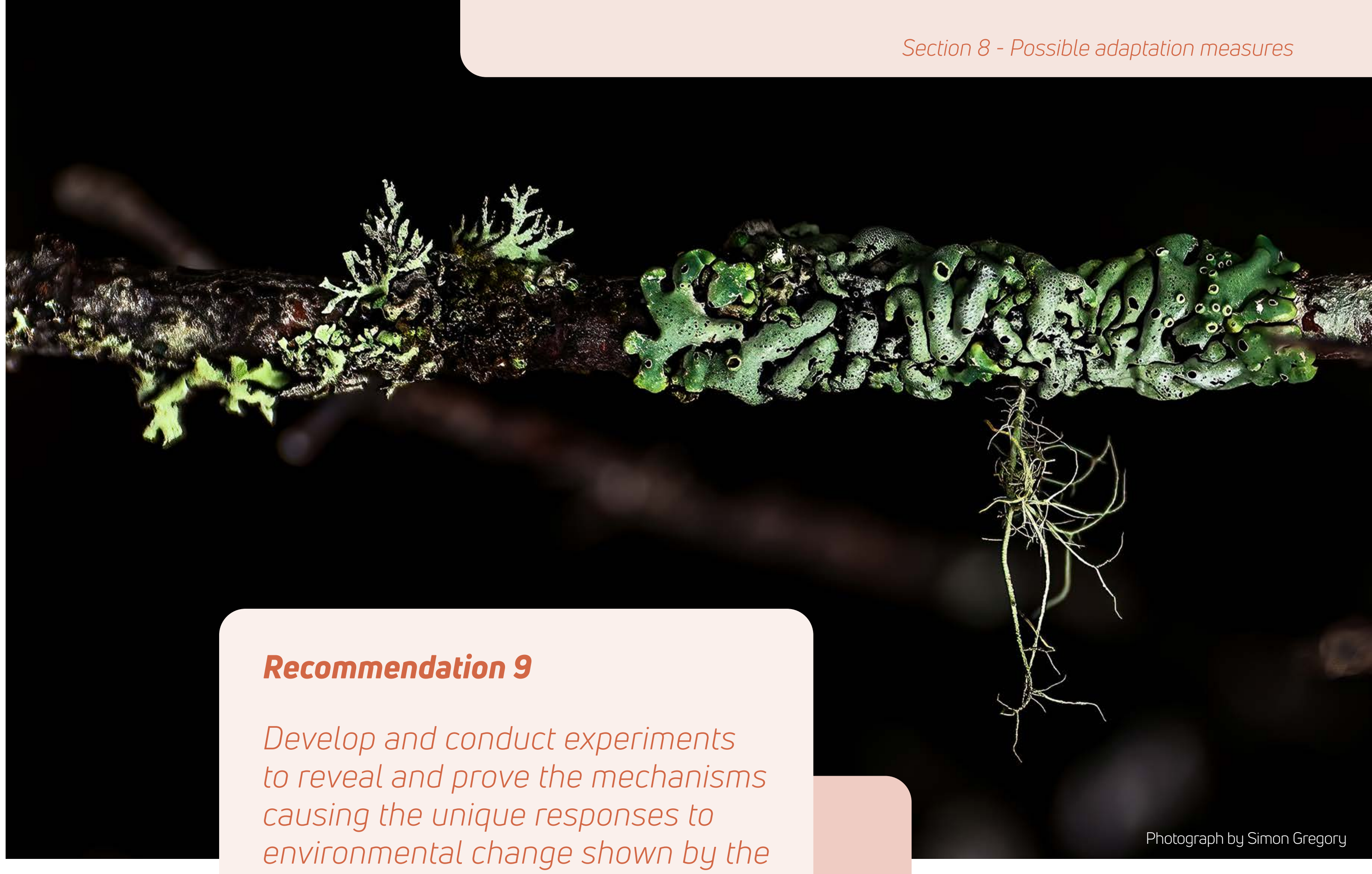
Possible adaptation measures

Tall eucalypt forests develop over long time intervals. Regenerating forests may not begin flowering intensively until they reach 25 years of age[35]. Long lead times will be needed to increase forest resilience to a warmer climate through genetic adaptation. There is a window of opportunity to get the evidence needed to prove and plan for implementing such an approach before a temperature tipping point is reached. The technical feasibility of implementing measures to increase the resilience of tall eucalypt forests to a warmer climate is only one element of an effective adaptation response. The policy settings and obtaining the social licence needed to implement measures to increase forest resilience also must be dealt with during that window of opportunity.

Understand the mechanism causing productivity (photosynthesis) to decline when temperatures exceed the optimum

The tall eucalypt forest at Warra responds to environmental change in ways not seen at other Australian sites. The different responses shown at Warra include:

- At above-optimum temperatures, declines in productivity occur when there is ample sunlight, and there is no evidence of any regulation to limit water loss by the forests[13].
- Unlike other sites in Australia, there is a lack of seasonal (winter / summer) acclimation to temperature of respiration[36] and photosynthesis[37]. Low sunlight in the winter is associated with this lack of acclimation[36].
- Productivity is much more sensitive to temperature than other temperate forests and woodlands[12]. The high temperature sensitivity at Warra more closely matches tropical forests and savannah forests (during their wet season), than temperate forests. The tropical forests and savannah forests (during their wet season) each have narrow temperature ranges compared with temperate forests and woodlands[12]. Warra also has a narrow temperature range.



Photograph by Simon Gregory

Recommendation 9

Develop and conduct experiments to reveal and prove the mechanisms causing the unique responses to environmental change shown by the tall eucalypt forests at Warra, and Tasmania more generally.

Discovering the mechanisms that lead to the responses to environmental change seen at Warra has important practical applications. Knowing the mechanisms can:

- give greater certainty to the best approaches to take for increasing the resilience the Tasmanian forests to a warming climate
- identify which are the most likely environmental drivers of genetic adaptation for greater resilience to a warmer climate
- identify traits and attributes that can be used to screen forests (including eucalypt plantations) elsewhere in Tasmania for their temperature sensitivity
- refine models used to predict the growth rates of Tasmanian tall eucalypt forests, such as the 3PG forest growth module in the FullCAM carbon accounting model

Hypotheses that could explain the responses to environmental change observed in the forest at Warra need to be developed. Those hypotheses would then need to be experimentally tested. The responses to environmental change shown by the tall eucalypt forest at Warra are novel. This novelty will help to develop studies that are prospective for funding and attractive for students. The strong alignment of the science with end-use (and end-users) adds to the prospectivity for funding.

Future tall eucalypt forests that are more resilient to warmer temperatures

Tall eucalypt forest that are more resilient to a warmer climate would be able to maintain productivity at higher temperatures and be less likely to cross temperature tipping points. This will require the optimum temperature for productivity of the forest be higher than it is now. It will also require the productive potential of the forest be comparable with levels that were reached before rapid warming began.

Three ways for increasing the resilience of the forest to warmer temperatures have been considered.

- Acclimatation of the existing forests. This approach is unlikely to work given the seasonal temperature acclimation of the forest at Warra is either very weak or absent[36,37]. There is also a lack of evidence of temperature acclimation in terrestrial ecosystems more generally[14].
- Introducing non-local genotypes that come from areas with a historical climate that better match the predicted future climate of the target area – so-called climate-adjusted provenancing[38]. This approach has been widely tested for forest restoration, particularly in drier areas. It may be risky for Tasmanian tall eucalypt forests though. There are two reasons for this. Firstly, the climate matching relies mainly on rainfall and temperature[39], neither of which are strong determinants of the key trait – high temperature sensitivity. The trait of high temperature sensitivity is linked to Tasmania's low annual temperature range experienced by tall eucalypt forests[6]. Secondly, non-local genotypes are ill-adapted to local pest and pathogen populations and seedlings have a high risk of suffering severe damage and high mortality[40].
- *In situ* enhanced natural selection[38] is the most prospective approach for two reasons. First, it will preserve evolved traits for exceptional productivity that developed in an environment where water is not limiting and the temperature range is small. Secondly, it preserves evolved adaptations to local pest and pathogen populations.

Enhanced natural selection involves the use of *in situ* genetic adaptation of tall eucalypt forests that are managed for shorter generation times and are screened to select genotypes that are adapted to warmer temperatures and culling genotypes that are not adapted to warmer temperatures (Box 2). Each new generation of tall eucalypt forest regenerated in a local area would only use

One-year-old stringybark (Eucalyptus obliqua) regeneration following harvesting and burning of the logging slash, Arve Valley, southern Tasmania.

Photo by Tim Wardlaw

seed from the previous generation that had been exposed to unusually warm temperatures during the main period of natural selection of that stand - typically the first 1-2 years of the regenerating forest when seedling competition is most intense[41].

> *The requirement for shorter generation times and selecting climate adapted genotypes will mean enhanced natural selection will be practicable only in production forests.*

Enhanced natural selection would represent a significant shift in the management, operation, and policy of eucalypt seed production. Future seed supply for regenerating tall eucalypt forests may extend beyond regenerating areas after harvesting to include restoration of areas in reserves. Significant additional costs can be expected, but this may be compensated if these climate change mitigation and restoration actions are eligible for credits in carbon, biodiversity and nature repair markets.

Enhanced natural selection will involve changes to sowing practices and the management of stands designated for seed production. Changes in sowing practices would be needed to facilitate natural selection. Designation of stands for seed production would be needed to protect, as seed production areas, those stands that experienced events that drive natural selection for greater tolerance to a warmer climate. Seed production areas could represent areas sown to high density (to facilitate natural selection), and that were exposed to much warmer than normal temperatures during the time the regenerating stand was undergoing intense competition.

The first generation of natural selection for tolerance of warmer temperatures may already exist in silviculturally regenerated forests that were exposed to high temperatures during their first 1-2 years. An analysis to identify years of high temperature anomalies in local areas coupled with sowing year mapping would enable 1st generation forests with natural selection for tolerance to warmer temperatures to be located.

Once designated, seed production areas would be prioritised for future seed production and managed accordingly. To make such fundamental changes to seed management, seed operations and seed policy would need to be informed by research designed to address the myriad of questions that will arise. Considerable negotiation and planning will be needed to oversee the knowledge needs (i.e., design and conduct of research) and the administrative, managerial and operational needs for a climate resilience seed production system.

There needs to be a better understanding of the quantum of benefits, if any, to be provided from enhanced natural selection because a climate resilience seed production system would be more complex and costly than current seed management. If enhanced natural selection is to provide meaningful gains in resilience within a useful timeframe we would need to find measurable gains in relevant traits after each generation exposed to selection events[7].

An increase in the optimum temperature for productivity would be one such relevant trait. Growth response curves computed from measurements of tree growth rates and temperature would detect shifts in the optimum temperature. Such measurements can be obtained relatively cheaply and quickly using sensors to automatically measure tree growth (dendrometers) and temperature (Box 2). Validating useful increases in optimum temperature for growth from a natural selection event would be particularly valuable if done in older (1970s and 80s) silviculturally regenerated forest areas that have reached the age when seed production begins. Older silviculturally regenerated forests with validated higher temperature optima for growth could be the initial climate-resilient seed production areas. Such seed production would be particularly valuable if done during the window of opportunity before temperature tipping points are reached.

Recommendation 10

Obtain evidence that enhanced natural selection is providing meaningful, and measurable, gains in resilience to warmer temperatures within relevant timeframes.

Box 2

What enhanced natural selection might look like

Regenerating a new generation of tall eucalypt forests by sowing locally collected seed is done after harvesting and burning the logging slash. In tall eucalypt forest areas available for harvesting, some patches (coupes) would be harvested and regenerated in most years. During the first 1-2 years after sowing, the young seedlings experience intense competition from neighbouring seedlings. A heightened proportion of seedlings that survive this period of intense competition may carry genes that help cope with the growing conditions at that time. If the growing conditions were hotter than normal, genes that are beneficial for coping with hotter conditions may become more common among the surviving seedlings. The opposite outcome might be expected if the growing conditions were cooler than normal.

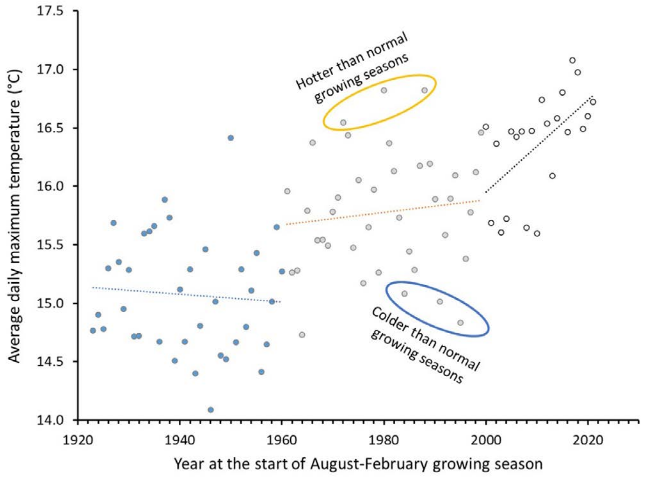


Figure 2. Average daily maximum temperature during the growing season (August-February) at Cape Bruny Lighthouse for each season between 1923-2022. Growing seasons during the initial 1-3 decades after the introduction of clearfell, burn and sow silviculture that had hotter or colder than normal temperatures are indicated. Further explanation of the data shown in Figure 2 is given in Appendix 1.2.

Figure 2 plots the average daily maximum temperature of the growing season (August-February) measured at the Cape Bruny Lighthouse (Tasmania). This weather station is part of Australia's network of reference sites for monitoring long-term trends in temperature. Cape Bruny also bounds the south-eastern extent of the range of the tall eucalypt forests in Tasmania – the "southern forests". Clearfall harvesting followed by burning and sowing (CBS) was introduced into the southern forests in the mid-1960s. In the first 2-3 decades of CBS there were hotter than normal seasons in 1972, 1980 and 1988. Patches of regenerating forest that were in their first or second growing season in one of these hotter than normal seasons might be better adapted to warmer conditions. Colder than normal years were experienced in 1984, 1991 and 1995. Patches of regenerating forest that were in their first or second growing season in one of these colder than normal seasons might be less well adapted to warmer conditions.

An adaptation response from exposure to warmer temperatures we might observe is a shift towards a higher optimum temperature for tree growth. Such a shift might be detected by measuring tree growth rates and air temperature for each growth period and graphing them together to produce temperature response curves. Tree growth rates can be measured using dendrometer bands that precisely measure small changes in tree circumference. Figure 3 shows a temperature response curve (in blue) of a sample of trees in a 70 year old (approx.) stand of *E. obliqua* near Hastings Chalet (Tasmania). Tree growth rates were measured using manual band dendrometers and temperature measurements were obtained from the nearby weather station at Hastings Chalet. A hypothesised increase in the optimum temperature for growth is shown by the orange line.

A network of dendrometers and temperature sensors could be used to get the measurements needed to produce temperature response curves. Such a network of dendrometer / temperature sensors could be set up to sample regenerating tall eucalypt forests that were selected to represent contrasting temperature conditions during their first 1-2 years after sowing. Using the temperature measurements from Cape Bruny Lighthouse such a contrast might be stands sown in 1972, 1980 and 1988 (hot growing seasons) and, stands sown in 1985, 1991, 1994 (cold growing seasons). The hypothesis to test would be that the optimum temperature for tree growth would be higher in forests that were regenerated in hot growing seasons than those that were regenerated in cold growing seasons. Testing this hypothesis would also give an indication of the size of the shift, if any, in the optimum temperature from one generation of natural selection for warmer temperatures.

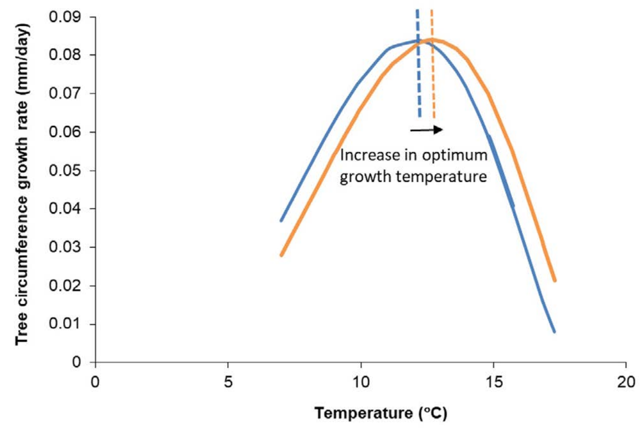
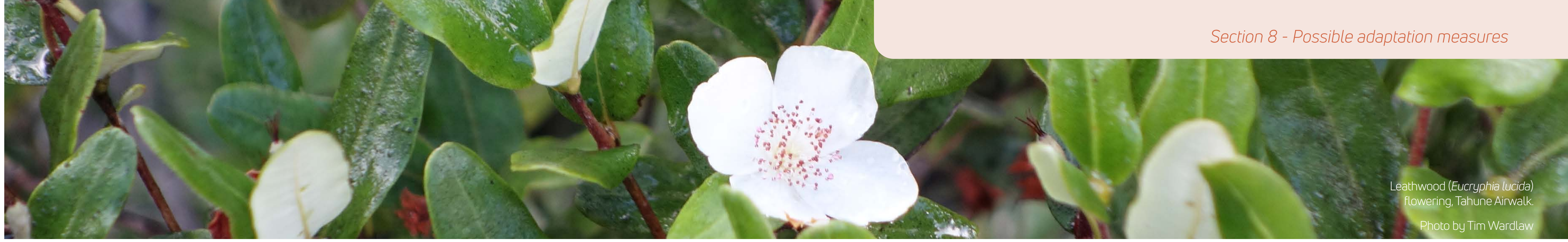


Figure 3. Plot of the relationship between measured growth rate and temperature measured using band dendrometers in a sample of 70 year-old *Eucalyptus obliqua* at Hastings, southern Tasmania. The blue line shows the relationship based on measurements, while the orange line shows a hypothesised increase in the optimum temperature for stem growth rates. Explanation of how the data shown in Figure 3 were obtained is given in Appendix 1.3.



Leathwood (*Eucryphia lucida*) flowering, Tahune Airwalk.
Photo by Tim Wardlaw

Forest policy is informed by the new knowledge of the impacts of climate change in tall eucalypt forests

The risk that a hotter and drier climate will have direct adverse impacts on the health and productivity of Tasmania's tall eucalypt has significant implications for forest policy.

Emissions reduction

Arguments to end logging in Tasmania's public native forest are increasingly focussed on the potential for carbon uptake and storage by forest reservation compared with greater utilisation of forest products provided from managed forests. Australia's (and Tasmania's) greenhouse gas inventories show large decreases in emissions from the LULUCF sector since 2012. That decrease in emissions corresponds with reductions in native forest harvesting and increases in the area of native forests protected from harvesting. This change in the LULUCF emissions profile is widely used as evidence in support of ending native forest logging as a measure to reduce net emissions[42]. As discussed in Section 6b, the FullCAM model used for LULUCF inventories is likely to overestimate the amount of carbon sequestered through forest growth in Tasmania's tall eucalypt forests that are experiencing warmer temperatures.

As discussed in Section 7b, increasing the resilience to a warmer climate of future tall eucalypts forests in Tasmania will be a critical adaptation response. Compared with the current generation of forests, a more climate-resilient future forest will:

- sequester more carbon at higher temperatures; and
- be less likely to cross a temperature tipping point.

Enhanced natural selection of local genotypes of the dominant eucalypt species is the most prospective approach for increasing climate resilience of future forests. Enhanced natural selection is only operationally feasible in native forests managed for wood production.

Any evidence-based decision on management of tall eucalypt forests to provide the greatest benefit for emissions reduction needs to take account of over-estimation of the predicted amount of carbon sequestered through forest growth, and changes in the climate-resilience of future forests.

Recommendation 11

Policy decisions on the optimum management of public tall eucalypt forest in Tasmania for sustaining multiple values takes into account: (i) the sensitivity of the current generation of tall eucalypt forests to warming temperatures; and, (ii) the capability for introducing greater resilience to warmer climate in future generations of tall eucalypt forests through enhanced natural selection.

Responses to mass mortality events in protected areas

Mass mortality events in tall eucalypt forests will pose considerable challenges if they occur within protected areas. If left alone, such events would result in the permanent loss of the eucalypt overstorey, and with it, a considerable loss of environmental and cultural values. To maintain canopy-forming eucalypts in the forest after mass mortality events will require seed falling on a seedbed beneath canopy openings to allow the next generation of eucalypts to survive and grow.

Previous episodes of mass mortality in tall eucalypt forests, such as regrowth dieback events in the 1970s and 80s occurred when most of the forests were dedicated as State forest. Sowing to create a new generation of trees in severely dieback-affected forest areas was facilitated by harvesting followed by burning of the slash to create seedbed.

Such practices were, and still are, permitted in areas available for wood production such as State forest (now the Permanent Timber Production Zone). But not in protected areas. Creating seedbed for a new generation of trees without an initial harvest to facilitate safe and effective burning has not been done in tall eucalypt forests. The 2019 bushfires have provided some insights into how tall eucalypt forests can burn under milder fire conditions[43]. Mild fire conditions allowed a low intensity ground fire rather than the fierce crown fire that is commonly associated with tall eucalypt forests. The insights gained from the 2019 bushfires could be the catalyst for beginning the thinking needed to identify and develop ways of safely introducing fire into tall eucalypt forest areas suffering mass mortality without an initial harvesting of the overstorey eucalypts.

We currently have no way of predicting when or where mass mortality events will occur. Decisions will need to be made about whether to, or not, restore the forest areas if they experience such mass mortality events. If restoration is to be attempted, how will it be done? Such decisions will be complex as there may be many stakeholders, including: international bodies; one or more tiers of government; the responsible and neighbouring land managers, NGOs and other community groups; Aboriginal people, and the public. To avoid non-decisions becoming *de facto* decisions to do nothing after mass mortality events, conversations need to be had and permissions given, well in advance of such events.

Recommendation 12

Develop a forest restoration policy and accompanying procedure to allow timely decisions to be made on whether to, or not, restore a new generation of canopy-forming eucalypts after mass mortality events in reserves.

Sustainable yield of high-quality eucalypt sawlogs

Use of tall eucalypt forests has made the dominant contribution to meeting the legislated supply of high-quality sawlogs. The most recent update of the sustainable supply of high-quality eucalypt sawlogs from crown forests[44] notes:

- A sharp transition in sawlog supply after 2026 when thinned and pruned eucalypt plantations will provide nearly 60% of the legislated volume of high-quality sawlogs.
- Large increases in forecasted sawlog yield after 2060. These increases are the result of anticipated genetic gains in plantations, and the next generation of regrowth forests reaching target rotation age.
- The "headroom factor"® has been removed from the sustainable yield.

Forest scene in eucalypt tall forests, Core 1-ha Plot, Warra SuperSite. Photo by Tim Wardlaw

As a headroom factor is no longer included in the sustainable yield calculation, there is no safety margin for reductions in yield until 2046: any losses in sawlogs volume will put pressure on the legislated supply. Increases in the risk of growth and timber volume losses from climate change have not been accounted for, yet those losses could be substantial. An audit of changes in the risks to the sawlog yield as the result of climate change could help quantify the scale of potential losses. Such an audit would be the precursor for any decisions on the need for measures to reduce risks or make allowance for losses to the legislated supply volume. The outcomes from Recommendation 5 should achieve most of what such an audit would provide. The outcomes of Recommendation 5 would also help inform an action identified by the audit of the sustainable yield report to update growth models and yield tables.

Communicate and educate on the effect that climate change is having on Tasmania's tall eucalypt forest

New discoveries about the threat that climate change poses to Tasmania's tall eucalypt forests challenge conventional wisdom and strongly held opinions.

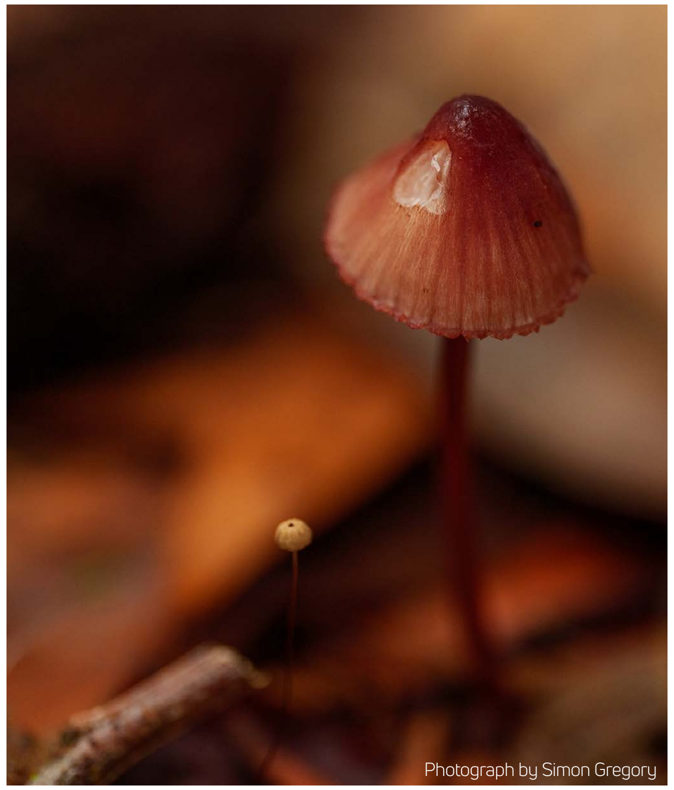
- The tall eucalypt forest at Warra in the TWWHA is responding to warmer temperatures and heatwaves in ways not seen before.
- Declines in productivity when temperatures rise above the optimum for the forest are much stronger in Tasmanian tall eucalypt forest than similar forests on the Australian mainland.
- Tasmania's cool, moist climate offers no buffer from warming temperatures.
- Reservation is not protecting the current generation of Tasmania's tall eucalypt forests from being impacted by climate change.
- Adaptation of future tall eucalypt forests to a warmer Tasmanian climate may depend on access to seed possessing improved heat-tolerance produced in forest areas managed for enhanced natural selection. Enhanced natural selection is only technically feasible to do in native forests managed for wood production.

The threat to Tasmania's tall eucalypt forests posed by a warming and drying climate has a high likelihood of resulting in very poor outcomes if no, or inappropriate, actions are taken. Many actions will be challenging because their premise threatens well-established positions, such as the security of the emissions reduction benefits provided by tall eucalypt forests that are in protected areas. Other actions will be challenging because their implementation may impose additional costs and complexity to managers, such as would be required for enhanced natural selection for resilience to a warmer climate.

Overcoming the challenges for action will need engaging, clear, and accurate information of complex science to be regularly communicated to diverse audiences. This will be most important for the youngest in our community who will shoulder much of the burden of dealing with the larger impacts from climate change we expect to see later in this century. We need to equip this younger generation with the skills and know-how that will, in the future, allow them to assemble evidence from large volumes of data and other information and use this evidence to make sound and effective decisions.

There are opportunities that we can capitalise on to help meet the challenges for communication and education in this contentious but critical issue.

- data-driven evidence made possible by using data from existing Tasmanian facilities that measure many of the key attributes needed to describe the status and trends of the local area:
  - atmosphere (Cape Grim Baseline Air Pollution Station)
  - climate (Tasmanian temperature reference sites managed by the Bureau of Meteorology, such as Cape Bruny Lighthouse)
  - forests - Warra LTER site
  - build on a well patronised tourist facility showcasing tall eucalypt forests - Tahune Adventures
  - make use of an existing institution that supports Tasmanian schools and teachers to engage with forest environments - Forest Education Foundation
  - draw on a very active and accessible forest research site, which has built an extensive knowledge base of tall eucalypt forests - Warra LTER site
  - draw on the strong linkages between science and forest management that has been the dominant driver of research done at Warra



Photograph by Simon Gregory

The forests themselves assist in communicating how climate change is affecting them. Their high productivity coupled with their high sensitivity to temperatures that rise above the optimum make it easy to see changes in carbon uptake / loss happening in real time (Box 3). Data from TERN flux stations[9] can be transmitted in real-time online where they can be freely accessed and used. There is enormous potential to use these data to develop novel ways engage and inform visitors to the forest (such as at Tahune Adventures) and to make the forest and its environment accessible to classrooms (such as by the Forest Education Foundation).

A strong physical connection has been established between Warra SuperSite and Tahune Airwalk – they are close to one another and are in both tall eucalypt forest. The Airwalk brings many visitors into the forest; the measurements and knowledge from Warra may be used to develop interpretive material about the forest to enhance the visitor experience.

Tahune Airwalk has a large space (Bluestone Shelter) that could be refurbished to host an interpretation centre to use real-time data from monitoring such as at Warra. For example, this data could be used to tell a story about "how the forest is feeling" under the same weather conditions the visitors to the Airwalk are experiencing. This experience could be the entry point to communicating how climate change is impacting Tasmanian forests; what options are available to help tall eucalypt forests adapt; and how well those options are working. There would be potential to develop a partnership with the University of Tasmania to use a climate change interpretation facility at Tahune as a laboratory to devise and test new ways to communicate climate change measurements to diverse audiences.

Recommendation 13

Develop opportunities for Tahune Adventures and Forest Education Foundation to use data and real-time measurements from Warra SuperSite to communicate and educate on the impact of, and responses to, a warming climate in Tasmania's tall eucalypt forests.

The Forest Education Foundation has used Warra as one of its outdoor classrooms for many years. The Foundation has also developed the Tasmanian Forest Education Plan[45] that helps to embed forest education into teaching programs within schools. School visits to forests are becoming more difficult to do because of the increasing burdens of cost, time, and administration. Easy access to data such as from the Warra provides an opportunity to bring the forest into the classrooms. Hands-on activities to allow schools to have their own long term monitoring activity in nearby forests or school ground trees could be developed as a "Forest in a Box" resource. The curriculum links in the Forest Education Plan, when coupled with measurements such as made at Warra and at school activity sites and will provide a great many opportunities make difficult concepts like climate change and forest management real and accessible.

There may be an opportunity to further strengthen the communication and education opportunities through a partnership with UNESCO. Warra is within the TWWHA, which UNESCO recently listed as their number one ranked property for annual carbon sequestration by forests. This may provide a platform to develop a partnership with UNESCO to use the measurements at the Warra LTER for research, education and communication about climate change and carbon sequestration by the tall eucalypt forest. UNESCO recently developed such a partnership with tertiary institutions in the Democratic Republic of Congo and the Belgian government to instal and run a flux tower in the Yangambi Biosphere Reserve as part of a monitoring and training hub[10].

Developing a forest climate change interpretation facility for visitors to Tahune Airwalk; and bring forest climate change into the classroom by the Forest Education Foundation, would be springboards for refining ways to communicate the science to diverse audiences. Evidence from the data these facilities use could showcase an example of how production forestry, conservation and tourism are working together to combat the impacts of climate change in tall eucalypt forests.

Recommendation 14

Seek a partnership with UNESCO to collaborate in showcasing the monitoring being done a Warra within the TWWHA and how that monitoring is being used to inform on impacts to tall eucalypt forests and guide the development of response actions.[9]

Mature tall eucalypt forest, Arve Road, southern Tasmania.

Photo by Tim Wardlaw

Box 3

Seeing productivity of the forest changing with the weather

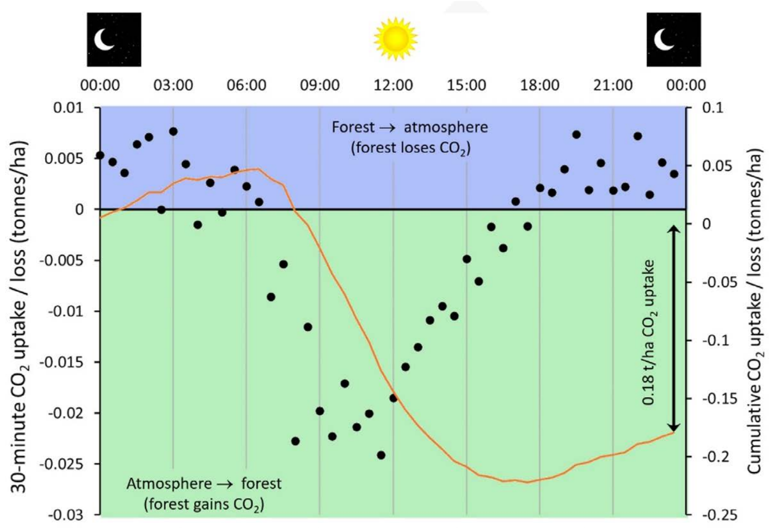


Figure 4. Plot showing the uptake (green zone) / loss (blue zone) of CO_2 by a hectare of forest at Warra over one day under ideal conditions. The black dots show the uptake or loss of CO_2 in each 30 minute period. The orange line shows the cumulative uptake or loss of CO_2 as the day progresses. Further explanation about how the data show in the graph was prepared is given in Appendix 1.4.

The *Eucalyptus obliqua* tall forest at Warra is very productive. When conditions are ideal, the forest can take up a large amount of CO_2 from the atmosphere and convert it into sugars. Ideal conditions for CO_2 uptake by the forest at Warra are simple to understand – there needs to be sufficient sunlight and mild temperatures. These forests grow in a wet environment, so water is rarely limiting.

The instruments at Warra that measure exchanges in CO_2 between the forest and the atmosphere can easily detect changes in those exchanges, even at intervals as short as 30 minutes. Figure 4 shows the carbon exchanges over 24 hours under ideal conditions for carbon uptake by the forest. Each dot on the graph represents the amount of CO_2 taken-up by, or lost from, one hectare of forest over a 30 minute period. Between midnight (00:00) and sunrise (06:30) and between sunset (18:00) and midnight (00:00) there is a net loss of CO_2 from the forest – CO_2 is moving from the forest into the atmosphere as the result of respiration. During the daylight hours between sunrise and sunset, there is a net gain of CO_2 by the forest – CO_2 is moving from the atmosphere into the forest as the result of photosynthesis. Note that the forest is also respiring during the daylight hours, but because the amount of CO_2 taken up by photosynthesis is much greater than the amount of CO_2 lost through respiration, we only see the net result – uptake of CO_2 by the forest. Tallying up the uptake or loss of CO_2 for each successive 30 minute (orange line) shows each hectare of the forest took up a total of 0.18 tonnes of CO_2 over the course of the day.

Figure 5 shows carbon exchanges (top graph), sunlight (middle graph) and air temperature (bottom graph) over 11 days in November 2017, just at the beginning of a record-breaking warm spell.

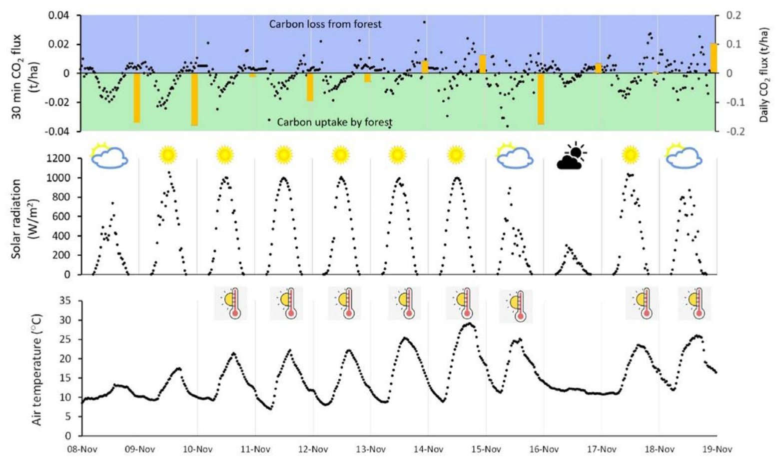


Figure 5. Plots showing half-hourly average of CO_2 flux, solar radiation and air temperature measured at the Warra SuperSite over an 11-day period in November 2017. Further explanation about how the data show in the graph was prepared is given in Appendix 1.4.

The forest took up a lot of CO_2 during the first two days (8-9 November) as shown by the CO_2 flux extending deep into the green zone (forest uptake) during the middle of the day (mid-way between the vertical lines). Each hectare of the forest took up nearly 200 kg of CO_2 on each of those two days (orange bars). Those two days had ideal conditions for CO_2 uptake – there was sufficient sunlight and temperatures were mild. By contrast there was little CO_2 uptake by the forest over the next five days (10-14 November). Conditions were sunny on each of those days, but temperatures were warm to hot and progressively increased on each successive day in the lead-up to a cold front passing over Tasmania on 15 November. After the cold front passed, overcast conditions through the day on 16 November limited CO_2 uptake, resulting in a net loss of CO_2 from the forest over the 24-hour period. Hot, sunny conditions returned for the final two days of the period (17-18 November). The forest had a net loss of CO_2 for each of those days.

Capabilities to deliver adaptation measures

Warra SuperSite

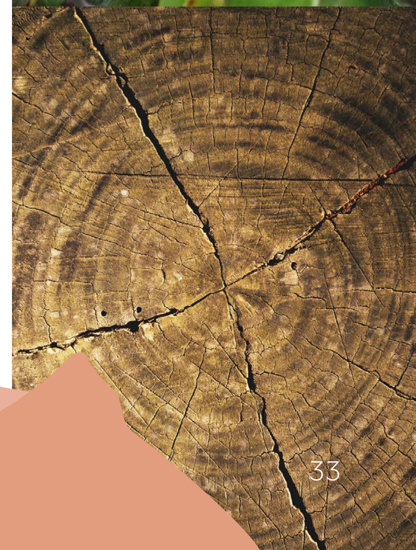
Measurements from the Warra flux tower and its companion 1-ha plot – together making-up the Warra SuperSite - allowed the detection of the unique response of the forest to heatwaves and, more generally, the forest's high sensitivity to warmer temperatures. Multi-site studies involving Warra and other SuperSites in Australia identified the most prospective pathway to improve the future climate resilience of Tasmania's tall eucalypt forests. Long term monitoring in Tasmania will continue to be central to proposed actions in response to the threat that a warmer and drier climate poses to Tasmania's tall eucalypt forests. The recommendations listed below each rely on data generated by the Warra SuperSite.

i. Calibration of alternative monitoring / measurement methods (Recommendation 2)
   - Necessary step towards the development of a satellite remote sensing method for broadscale monitoring of the productivity of tall eucalypt forests. Would provide a more explicit alternative to the current modelling approach used to account for forest growth in greenhouse gas inventories.
   - Necessary step to allow tree growth rates measured by dendrometers to be related to carbon uptake / loss by the tall eucalypt forest at Warra. Once done, data from a distributed dendrometer network can be used to test key forest responses to climate such as shifts in temperature optima for productivity (as evidence for natural selection).

ii. Fulfil monitoring obligations for the management of TWWHA (Recommendation 3)
   - Help fulfil requirement for periodic reporting to the World Heritage Committee on the state of conservation and management of the tall eucalypt forests within the TWWHA.
   - Provide early evidence of changes in the way the tall eucalypt forests are responding to future extreme weather events, particularly heatwaves. Will be critical in understanding what crossing a temperature tipping point will mean for tall eucalypt forest in the TWWHA.

iii. Refine / verify carbon accounting model predictions for growth rate of Tasmania's tall eucalypt forests (Recommendation 4)
   - Use relationship between forest productivity and temperature established from measurements at Warra to calibrate the 3PG forest growth module of FullCAM.
   - Verify estimates of forest growth modelled within the re-calibrated FullCAM with direct measurements of forest productivity.



iv. Synthesis of knowledge on tall eucalypt forest biodiversity to identify habitats and taxa at risk from climate change (Recommendation 7)

- Contextual knowledge generated from over 200 peer-reviewed journal publications are available (via the Warra web site – www.warra.com).
- Extensive biodiversity datasets (and metadata) from 25 years of studies at Warra LTER are accessible for re-use through TERN's data discovery portal.

v. Focal point to leverage and support research to understand the mechanism of the forests response to warming temperatures (Recommendation 9)

- Warra has had a high success rate in attracting research grants, particularly from the Australian Research Council. The close involvement of forest managers in identifying research needs to support management (i.e., strong pathway to adoption) has assisted in this.
- TERN's network of forest SuperSites has strong working linkages to facilitate national studies. Importantly, that network of SuperSites has already generated a large body of accessible and well curated data that can be interrogated for newly-framed research questions.
- Warra is a very accessible research site, located 90 minutes from Hobart. Accommodation nearby (at Tahune Airwalk) provides a good base for interstate and international scientists to use when conducting research in Warra.

vi. Obtain evidence of gains in resilience to warming temperatures from enhanced natural selection (Recommendation 10)

- The combination of flux measurements (carbon, water and energy) and tree growth measurements (via dendrometers) at Warra SuperSite will provide the necessary step to relate the dynamics of tree growth with the dynamics of carbon uptake / loss.
- Established relationships between growth / GPP dynamics are needed for assurance that growth response to temperature relationships developed from growth measurements are comparable with GPP responses to temperature. This will ensure that optimum temperature for growth of a stand can be defined together with the sensitivity to growth rates to departures from optimum temperature. These two attributes of growth response to temperature are then used for comparisons among stands to test hypotheses (of adaptation to warmer temperatures through natural selection) using designed experiments.
- Warra will also serve as the baseline reference site for growth / GPP relationships with temperature to compare with growth – temperature relationships established, using dendrometry, at other sites as part of a designed experiment.

vii. Support evidence-based decisions on safest way to manage Tasmania's tall eucalypt forests for climate change (Recommendation 11)

- Will bring together outcomes from Recommendations 4 (improved calibration of FullCAM for Tasmanian tall eucalypt forests) and 10 (evidence of adaptation to warmer climate through natural selection). Both recommendations rely on measurements made at Warra SuperSite.

viii. Support development of policy for restoration of degraded tall eucalypt forests in reserves (Recommendation 12)

- Ongoing measurements from Warra SuperSite displayed at Tahune Airwalk, and more widely, will help to maintain a high visibility of the threat that a warming climate is posing to the tall eucalypt forests in the TWWHA.
- Trends in forest health and productivity generated from ongoing measurements from Warra will be a reminder of the approaching risk of a tipping point as the forest becomes increasingly maladapted to the warmer climate.

ix. Use monitoring data for public communication and education about the impact of climate change on Tasmania's tall eucalypt forests (Recommendations 13 and 14).

- Opportunity to create a unique climate change interpretation facility and forest education package that uses measurements made at the Warra SuperSite to:
- Show how sensitive the forests are to a warming climate and how much less the forest enjoys warm days than do the visitors to the forest.
- Use other unique climate change measurements made in Tasmania to show how CO_2 pollution from our burning of fossil fuels is building up in the atmosphere (Cape Grim Baseline Air Pollution Monitoring Station), and how air temperatures have changed over the past century (weather station at Cape Bruny Lighthouse).
- Using tree growth measurements to show how production forests may be incubators for developing future tall eucalypt forests that are more tolerant of a warmer climate.
- Be the catalyst for the community to begin to think about how protected areas would change if tall eucalypt forests begin to die as the result of the climate becoming too hot for the current generation of the forest. This could initiate community input into if and how restoration might be done.
- Be a laboratory to explore and refine ways for communicating climate change and forest management to a wide audience with diverse backgrounds.
- Develop a partnership with UNESCO to showcase work on highlighting the climate threat to the tall eucalypt forests in the TWWHA and generating a community discourse on adaptation options.

Recommendation 15

Leverage the value of data from Warra SuperSite by packaging projects that use Warra data to address managing climate change risks to Tasmania's tall eucalypt forests.

Specialist expertise

Specialist operational expertise in managing forest health, provides the knowledge and know-how needed to detect, diagnose, evaluate, and develop approaches for management of new and emerging threats to the health of forests. This report is an example of that knowledge and knowhow being applied to a newly discovered threat.

For the first time in 50 years, Tasmania is without such expertise. This lack of expertise is compounded by the additional challenge that Tasmania's unique forest growing environment poses many threats to the health of Tasmania's forests, which behave idiosyncratically in ways not seen in forests elsewhere. It highlights the risk of appling knowledge gained from managing forest health threats elsewhere to Tasmanian situations.

Specialist knowledge and know-how needed to effectively manage threats to the health of Tasmania's forests need to be acquired from on-the-job learning. Developing ways to manage the threat that a warming climate poses to Tasmania's tall eucalypt forests provides an excellent opportunity for on-the-job learning for a new generation of forest health experts. There is a narrow window of opportunity for mentoring a new generation of specialist expertise in Tasmanian forest health management. The last link to the 50 years of accumulated knowledge and know-how of forest health management in Tasmania is the author of this report, who has reached retirement age. The recently established Australian Forest and Wood Innovations, hosted by the University of Tasmania, may provide a springboard to train a new generation of operational forest health management expertise for Tasmania.

Developing the next generation of expertise in operational forest health management first requires an appropriate organisation agreeing to host that expertise. Such an organisation would ideally have: (i) strong linkages to operational forest management; (ii) strong scientific motivation with a capacity to develop multi-disciplinary collaborations; (iii) responsibilities that extend to public and private forests as well as production and conservation forests. Currently, the Forest Practices Authority (FPA) best meets those criteria. The FPA also recently conducted a review of the impact of climate change and implications for forest practices.

Recommendation 16

Develop a model to fund, rebuild and sustain specialist expertise in operational forest health management in Tasmania.

Resources

No funding has been provided to understanding the vulnerability of Tasmania's tall eucalypt forests to a warmer climate. The knowledge that has been gained since the vulnerability was first documented in 2016[46] has been self-funded by the author of this report.

Delivering the 16 recommendations outlined could be done within a total budget of AU$5M spread over the next five years. That amount represents a fraction of the value of annual impacts likely to be experienced in the latter half of this century if no action is taken now. It is worth noting that many of the recommendations that need funding align with priorities of the AFWI. This alignment provides the opportunity to attract funds from AFWI on a cost-sharing basis. Recommendations that are aligned with AFWI priorities are identified in "Implementation of recommendations"

Implementation of recommendations

The 16 recommendations fall within five principal activities: data provision, greenhouse gas accounts, conservation, forestry, and communication (Table 1). For a recommendation to be implemented, a stakeholder, or group of stakeholders, will need to drive the process. Potential stakeholders have been proposed for each of the 16 recommendations that have been made. Those stakeholders have been proposed based on having responsibilities in areas shown by an activity grouping into which the recommendation fits (Table 1).

Four of the recommendations - 1, 6, 7, and 16 - are stand-alone and have no dependency on any other recommendation for their implementation.

Nine of the recommendations are identified as requiring research for their implementation. All but one of those recommendations requiring research are forestry related and might meet the criteria for funding through the AFWI on a cost-sharing basis with stakeholders. The projects that are proposed for the implementation of the recommendations align well with the priorities for AFWI[11] and for University of Tasmania as a research provider to develop and deliver those research components. To proceed down this path will initially require developing an expression of interest for the portfolio of research projects. To assist in doing this, potential project leaders have been proposed. The next step will be to liaise with those potential project leaders to gauge their interest and capacity to being involved in engaging with stakeholders and developing detailed research proposal.

Finally, the expected outcome(s) from implementing a recommendation has been suggested.

Stakeholders, dependencies, research need, research provider and expected outcomes are summarised on the following pages for each of the 16 recommendations.

Table 1. Alignment of stakeholders with activity groups (cells shaded dark orange) and recommendations (cells shaded light orange). Stakeholders have been sorted based on the scope of their responsibilities in areas identified in the activity grouping. Recommendations requiring research as part of their implementation are indicated with "R", or "RF", in the case of research that potentially aligns with priorities of the AFWI.

Stakeholder	TERN	UTas	ReCFIT	DCCEEW	UNESCO	PWS	DNRE	FPA	STTas	PFT & Industrials	TFFPN	Tahune & FEF	Tourism Tas
Activity group													
Data provision	●	●											
GHG accounts			●	●									
Conservation				●	●	●	●	●	●	●			
Forestry							●	●	●	●	●		
Communication	●	●	●	●	●	●	●	●	●	●	●	●	●
Recommendation													
1			○										
2 (RF)			○				○		○				
3	○	○		○	○	○							
4			○	○							○		
5 (RF)							○		○				
6 (RF)									○	○	○		
7 (RF)				○		○	○	○	○				
8									○	○			
9 (RF)							○	○	○				
10 (RF)							○	○	○				
11 (RF)			○	○		○	○		○				
12 (R)				○	○	○	○		○				
13 (RF)	○					○	○		○		○	○	○
14	○			○	○	○	○					○	○
15	○		○	○	○	○	○		○			○	
16 (CB)		○					○	○	○	○	○		

See the full list of recommendations on page 4

Section 9 - Implementation of recommendations

Relevance of recommendations

Recommendation 1

1.1. Stakeholder(s): State Growth – ReCFIT
1.2. Dependency: none
1.3. Research required for implementation: no.
1.4. Potential research provider: N/A
1.5. Expected outcome: government policy to support investments in developing and adopting responses to reduce the risk to tall eucalypt forests from the direct impacts of climate change.

Recommendation 2

2.1. Stakeholder(s): State Growth – ReCFIT; DNRE (Forests), STTas
2.2. Dependency: measurements from Warra to calibrate relationships for tree growth rates (dendrometry) and forest productivity (remote sensing).
2.3. Research required for implementation: Yes.
2.4. Potential research provider: UTas - Kathy Allen (lead for dendrometry), Arko Lucieer (lead for remote sensing).
2.5. Expected outcome: greater certainty in predictions of the impact that projected changes in temperature will have on the productivity and health of Tasmania's tall eucalypt forests.

Recommendation 3

3.1. Stakeholder(s): UTas, TERN, PWS, DCCEEW, UNESCO
3.2. Dependency: ongoing funding support from Commonwealth government (via National Collaborative Research Infrastructure Scheme).
3.3. Research required for implementation: no
3.4. Potential research provider: no but UTas continues to be the contracted site operator.
3.5. Expected outcome: monitoring obligations are met. Changes to the conservation status of tall eucalypt forest within the TWWHA are detected in a timely way.

Recommendation 4

4.1. Stakeholder(s): DCCEEW, State Growth-ReCFIT.
4.2. Dependency: Recommendation 2.
4.3. Research required for implementation: no
4.4. Potential research provider: N/A
4.5. Expected outcome: more accurate estimates of the contribution of forest growth to net emissions by the LULUCF sector in the Tasmanian and National GHG inventories.

Recommendation 5

5.1. Stakeholder(s): STTas, DNRE (Forests)
5.2. Dependency: Recommendation 2.
5.3. Research required for implementation: Yes
5.4. Potential research provider: UTas – Peter Love (lead for modelling future temperature conditions throughout the Tasmanian range of tall eucalypt forests)
5.5. Expected outcome: predictions of future sustainable yields from tall eucalypt forests account for the impact of a warmer climate giving confidence that wood supply will match investments in wood processing.

Recommendation 6

6.1. Stakeholder(s): STTas, Tasmanian private plantation owners/managers, Private Forests Tasmania, TFFPN
6.2. Dependency: none
6.3. Research required for implementation: yes
6.4. Potential research provider: UTas – Mark Hovenden (lead for eddy covariance to develop temperature – productivity relationships in *E. nitens* plantations); Kathy Allen (lead for dendrometry to develop temperature – growth relationships for *E. nitens* plantations)
6.5. Expected outcome: confidence of the resilience of E. nitens plantation to a warming climate or an early warning of the vulnerability of *E. nitens* to a warming climate that enables adaptation options to be identified and implemented before severe impacts appear.

Recommendation 7

7.1. Stakeholder(s): DNRE, STTas, FPA, DCCEEW
7.2. Dependency: none
7.3. Research required for implementation: yes
7.4. Potential research provider: UTas – Sue Baker (lead for synthesis of Warra biodiversity studies)
7.5. Expected outcome: habitats developing in tall eucalypts and biodiversity dependent on those habitats that are at greatest risk from a warming and drying climate are identified.

Recommendation 8

8.1. Stakeholder(s): STTas, Private forest/ plantation owners and managers, Private Forests Tasmania
8.2. Dependency: Recommendations 2, 4, 5, 6 and 7
8.3. Research required for implementation: none
8.4. Potential research provider: N/A
8.5. Expected outcome: better information to underpin decisions on the appropriate levels of investment to understand and manage the risks to tall eucalypt forests posed by a warming climate.

Recommendation 9

9.1. Stakeholder(s): STTas, DNRE, FPA
9.2. Dependency: Recommendations 2 and 3
9.3. Research required for implementation: yes
9.4. Potential research provider: UTas – Mark Hovenden (lead for ecophysiology studies)
9.5. Expected outcome: greater certainty in predicting responses of Tasmania's tall eucalypt forests to projected future climate.

Recommendation 10

10.1. Stakeholder(s): STTas, FPA, PWS, DNRE
10.2. Dependency: Recommendations 2 and 3
10.3. Research required for implementation: yes
10.4. Potential research provider: UTas – Kathy Allen, (lead for dendrometry to develop growth rate – temperature relationships), Mark Hovenden (lead for understanding relationship between growth rate [from dendrometry] and forest productivity [from eddy covariance] measurements).
10.5. Expected outcome: quantify changes in temperature optima for growth in stands exposed to warmer temperatures during intense competition period of stand development. Inform decision on policy and for investments in research to develop a seed production system based on *in situ* enhanced natural selection.

Recommendation 11

11.1. Stakeholder(s): DNRE, PWS, STTas, State Growth (ReCFIT), DCCEEW
11.2. Dependency: Recommendations 2, 4, 10 and 12
11.3. Research required for implementation: yes
11.4. Potential research provider: UTas – Richard Eccleston (lead for policy evaluation)
11.5. Expected outcome: policy for optimum management of Tasmania's tall eucalypt forests that allows the provision of multiple values in a future warmer climate.

Recommendation 12

12.1. Stakeholder(s): PWS, DCCEEW, UNESCO, DNRE, STTas, private forest owners and managers.
12.2. Dependency: Recommendation 10
12.3. Research required for implementation: yes
12.4. Potential research provider: UTas – Richard Eccleston (lead for policy development), Mark Hovenden (lead for developing regeneration procedures), David Bowman (lead for developing fire regimes to allow regeneration in degraded tall eucalypt forests).
12.5. Expected outcome: policy and procedures for restoration are widely accepted by stakeholders and interested parties well in advance of the need for their use.

Recommendation 13

13.1. Stakeholder(s): Tahune Adventures, STTas, PWS, DNRE, Tourism Tasmania, TFFPN
13.2. Dependency: Recommendation 3, Recommendation 9
13.3. Research required for implementation: yes
13.4. Potential research provider: UTas – Tim Wardlaw (provide scientific knowledge), Libby Lester (lead for social change communication), Martin Walch (lead for visual communications),
13.5. Expected outcome: trusted and easily understood source of information about the impact of climate change on Tasmania's tall eucalypt forests and of the development of actions to improve the resilience of future tall eucalypt forests to a warmer climate.

Recommendation 14

14.1. Stakeholder(s): TERN, PWS, DCCEEW, UNESCO
14.2. Dependency: Recommendation 13
14.3. Research required for implementation: none
14.4. Potential research provider: N/A
14.5. Expected outcome: increase the profile (internationally, nationally, locally) of the threat posed by a warming climate to Tasmania's tall eucalypt forests within the TWWHA to encourage public engagement and involvement in developing response actions.

Recommendation 15

15.1. Stakeholder(s): NCRIS, TERN, State Growth (ReCFIT), DNRE, PWS, DCCEEW, STTas, Tahune Adventures, UNESCO
15.2. Dependency: Recommendation 3.
15.3. Research required for implementation: none
15.4. Potential research provider: N/A
15.5. Expected outcome: support for the long-term funding for TERN and the operation of its facilities.

Recommendation 16

16.1. Stakeholder(s): FPA, UTas, DNRE, STTas, PFT, TFPPN
16.2. Dependency: none
16.3. Research required for implementation: none
16.4. Potential research provider: N/A
16.5. Expected outcome: specialist expertise in the operational management of the health of Tasmanian native forests and plantations is sustained and accumulated knowledge and know-how from five decades of specialist expertise is passed on.

Photograph by Nicolas Rakotopare

What will success look like?

Knowing what failures we avoid highlights what successes bring.

The first failure we avoid is the long-term over-estimation of forest productivity through ignoring the effect that a warming climate has on productivity. This will result in having to make disruptive, large and rapid adjustments (write-downs) to the amount of emissions reduction we claim, natural capital, and wood supply. We can avoid this poor outcome if we: (i) accurately define the extent of the vulnerability to warming temperatures in tall eucalypt forests throughout Tasmania; and (ii) if necessary, amend forest growth models and use the more accurate predictions to adjust for true levels of carbon emissions, natural capital and sustainable wood supply. Additional success will occur if, after making the downward adjustments, we can begin to turn-around the declines in forest growth through introducing effective adaptation measures.

The second failure we avoid is being unprepared for mass eucalypt deaths in tall eucalypt forests, including those in reserves and the TWWHA, as the result of increasingly regular heatwave events. This would increase the risk that tall eucalypt forests would transform to lower stature forests causing a large and permanent reduction in carbon stocks and jeopardising one of the outstanding universal values of the TWWHA. These grim outcomes can be avoided if we have planned for the eventuality of mass tree deaths from a warming climate and have an endorsed suite of response actions ready to deploy. We will have developed the technical capabilities and resources, including stores of climate-adapted seed, to restore tall eucalypt forest areas that have suffered mass tree deaths. Policy settings will support such responses and we will have obtained the social licence and necessary permissions to restore affected tall eucalypt forest areas.

Success will need the community to think and talk about tall eucalypt forests differently. The tools of forestry, which allow sustainable harvesting of tall eucalypt forests, may also be crucial in helping tall eucalypt forests to persist in a future hotter world. If the practical effectiveness of enhanced natural selection can be verified, the tone of what is communicated about the threat that a warming climate poses to tall eucalypt forests changes from a story of doom to a story of hope. Hope will be important to drive community and institutional support to have adaptation measures appropriately resourced and given the permissions that will allow restoration in reserves, if required. The global status of tall eucalypt forests driven by their exceptional productivity and size, means Tasmania could expect considerable kudos if it can successfully increase the resilience to a hotter climate of its future tall eucalypt forests.

Appendix 1. Explanation of data used in examples

Appendix 1.1. Explanation of data used in Figure 1

The data used in Figure 1 originated from the TERN eddy covariance flux tower at Warra and its other SuperSites (https://www.tern.org.au/tern-land-observatory/tern-ecosystem-processes/).

Raw 30 minute flux, CO_2 storage and climate data were processed by the standard TERN OzFlux QA/QC processing stream using PyFluxPro Version 3.4.8 software. CO_2 fluxes adjusted for storage (=NEE) were computed at the mid-stage (level 3). u* thresholds were computed for each year of records using the moving-point test (MPT) method. The u* value for each 30 minute record was tested against the computed u* threshold and if below threshold the NEE value was replaced with a modelled estimate[48]. At the final stage of data processing (level 6), gap-filled net ecosystem exchange (NEE) data were partitioned into gross primary productivity (GPP) and ecosystem respiration (ER).

The quadratic function modelling the relationship between GPP and temperature for Warra in Bennett et al 2021 (Table 2) was used to generate the GPP ~ temperature response shown in Figure 1. The quadratic function was:

$GPP = -0.09Ta^2 + 3.062Ta + 3.438$, where Ta = air temperature

The relationship between ER and temperature represents the average value of nocturnal CO_2 flux- Fc- (after u-star filtering), in each 2°C bin of air temperature between 2-30°C. Averages of u-star filtered Fc for each temperature bin was calculated using the analysis of variance procedure in Statgraphics Centurion.

C sink for each temperature bin was calculated as the difference between GPP and ER.

The average daily temperature range for the summer period shown in Figure 1 was extracted directly from Figure 2 for Warra (TMF-Wrr)[12].

Appendix 1.2. Explanation of data used in Figure 2

Daily maximum temperature records measured at Cape Bruny Lighthouse (Station number 094010) between 1923-2020, and Cape Bruny (Station number 94198) between 1997-current, were accessed from the climate data online on the Bureau of Meteorology's web site. A full set of records 1 January 1923 – 28 February 2023 were created by appending measurements from Cape Bruny to those of Cape Bruny Lighthouse from 1 January 2021. A linear regression was done to the calculate the relationship between maximum daily temperature measurements from Cape Bruny with those from Cape Bruny Lighthouse. Measurements for the overlapping period of the two stations between 17 May 1997- 31 December 2021 were used in the linear regression. Gaps in the daily records were filled using records from nearby stations – Hastings Chalet (Station number 094027), Dover (Station number 94020) or Hobart – Ellerslie Road (Station number 094029). Linear regressions of the daily maximum temperature records of Cape Bruny Lighthouse and each of the three stations used for gap filling were calculated and used to translate records to Cape Bruny Lighthouse-equivalence.

Simple averages were calculated from all daily maximum temperature records for each growing season. Growing seasons were defined as days between 1 August and 28(29) February of the following year. A timeseries plot of growing season average maximum daily between 1923-2022 was made. Three distinct "temperature regimes" were visually apparent in the timeseries plot: 1923-1958 (stable baseline); 1960-1999 (step increase in temperature), 2000-onwards (steady increase in temperature). Linear trendlines were fitted to records in each of the three periods to highlight these temperature regimes.

The three growing seasons with highest average daily maximum temperature in the "step increase" temperature regime period were identified as were the three growing seasons with the lowest average daily maximum temperature in the "step increase" temperature regime period.

Appendix 1.3. Explanation of data used in Figure 3

Stem circumference growth rates were obtained from aluminium manual band dendrometers fitted at breast height (1.3 m) to 21 *E. obliqua* trees in 66-year-old regrowth forest approximately 800m south-east of the Hastings Caves Chalet. The 21 trees spanned the range of tree size classes present in the forest. Table 2 gives details of the 21 trees.

Table 2. Characteristics of 21 Eucalyptus obliqua *trees near Hastings Chalet that were fitted with band dendrometers.*
**Diameter measured at breast height (1.3m) over bark*
#Crown dieback rating[47]

Canopy class	Number of trees	Average diameter (cm)*	Average primary crown dieback#	Average percent epicormics#
Dominant	5	61.7	18	22
Co-dominant	10	57.4	26	25
Sub-dominant	4	50.3	40	52.4
Suppressed	2	29.9	60	25

The dendrometer bands were fitted in July 1980 and were read at approximately monthly intervals until March 1983. A total of 30 measurements (29 measurement intervals) were obtained during the 2.5 year experiment. Change in circumference between each consecutive measurement was calculated and converted to circumference growth rate by dividing by the number of days between the measurements. Average circumference growth rate for each of the 29 measurement intervals were calculated. Only the 15 dominant and codominant trees were used to calculate the averages.

Daily mean temperatures were obtained from the Bureau of Meteorology station at Hastings Chalet (Station number 094027). The average of the daily mean temperatures for each of the 29 measurement intervals was calculated. A non-linear regression was fitted to the data. The regression model had the form:

$CGR = (a(T-b)*(1-e^{c(T-d)}))^2$

where CGR = circumference growth rate and T= average temperature

The fitted model was:
$CGR = (0.0527(T-2.3367)*(1-e^{0.1362(T-18.185)}))^2$

The example curve demonstrating a 0.7ºC shift in the optimum temperature for growth was generated by adding 0.7 to the value of each average temperature record in the dataset to generate a revised CGR.

Appendix 1.4. Explanation of data used in Figures 4 and 5

All measurements were made by instruments mounted at the top of an 80m tower at the Warra SupserSite (43° 5'42.98"S, 146°39'19.01"E). A full description of the instruments, measurements and processing of the data are given in Wardlaw (2022)[13]. 30 minute data used in the example were extracted from a 2013-2021 compilation file that had been processed to Level 6 using PyFluxPro Version 3.4.8. Three variables were extracted – Fco2 (CO_2 flux corrected for storage), Fsd (downwelling shortwave radiation), Ta (air temperature). The unit of Fco2 was converted from mol/m^2/sec to tonnes/ha over the 30 minute period. 30 minute values of Fco2 were tallied over the full day to measure daily CO_2 uptake or loss.

Endnotes

① Photosynthesis involves using the energy from sunlight to convert CO_2 from the atmosphere into plant sugars. Respiration involves all living cells of all air-breathing organisms present in the forest (plants, animals and microbes) using those plant sugars for converting to energy (with the release of CO_2,) needed to drive essential life processes.

② Carbon starvation is the term applied to when sugar production from photosynthesis is insufficient to maintain sufficient food reserves in the trees needed to maintain life processes.

③ Page 44 in: DPIPWE 2016, *Tasmanian Wilderness World Heritage Area Management Plan 2016*, Department of Primary Industries, Parks, Water and Environment, Hobart

④ With approximately 3°C of warming: (i) Bowman et al. (2014, Global Change Biology 23: 925-934) estimated a decline in tree growth of 22%; (ii) heatwave events like the 2017 event will be an annual event. Wardlaw (2018, unpublished report) measured a 50% reduction in productivity in the growing season containing the 2017 heatwave event compared with the previous growing season with close to normal temperatures.

⑤ Statement by Dr Michael Burger, CEO of PEFC International, at the *Wood you like to know* conference, Brisbane, 30 March 2023.

⑥ These findings are detailed in an oral presentation entitled *TERN-enabled research to diagnose causality of the high sensitivity to warming temperatures in* Eucalyptus obliqua *tall forest at Warra; and to inform management* given by Tim Wardlaw at the 2023 TERN Science Symposium, Brisbane 26-27 July 2023 (https://www.youtube.com/watch?v=n-Gghk1fY9M).

⑦ A natural selection event is considered to have occurred if regenerating seedlings are exposed to unusually high temperatures during the period when there is high competition among the seedlings.

⑧ A safety margin (expressed as a percentage figure) to absorb discounts to the predicted yields arising from changes to the area available for harvest or to yields to meet conservation requirements under the Forest Practices Act.

⑨ The original flux tower at Warra collapsed in September 2021 after a large tree fell across supporting cables, interrupting the dataflow commenced in 2013.

⑩ https://www.unesco.org/en/articles/yangambi-biosphere-reserve-congo-basin-become-knowledge-hub-climate-and-biodiversity

⑪ https://www.agriculture.gov.au/agriculture-land/forestry/national/australian-forest-and-wood-innovations#research-themes

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The Warra research site is about 8 km west of the Tahune Airwalk on Manuka Road in Tasmania.

About the Author

Tim Wardlaw has a doctorate in forest pathology and has authored or co-authored more than 100 peer-reviewed, applied research papers in the fields of forest health and conservation management. His career has spanned 40 years, most of it spent with Forestry Tasmania and its predecessor the Forestry Commission of Tasmania. His primary responsibility was to provide the specialist expertise that underpinned operational management of the health of Tasmania's multiple-use public forests. In that role he was involved in the development and refinement of practices for the management of all the major pests and pathogens affecting the health of Tasmania's forests. He has been at the forefront of forest health surveillance in Australia and established formal health surveillance of Tasmania's public multiple-use forests in 1997. This program is one of the longest running forest health surveillance programs in the country. He has shared his expertise in forest health management through capacity-building projects in many countries in the Asia-Pacific region.

While managing the conservation and biology research program at the Warra Long-Term Ecological Research site, he successful applied to get Warra selected as one of 16 "SuperSites" in the NCRIS-enabled Australian national observatory for monitoring its terrestrial ecosystems - TERN. He has been Principal Investigator at the Warra SuperSite since its inception in 2010. Tim has had a career-long interest in the role that climate plays in forest heath, both directly and through altering the activity of pests and pathogens. The establishment of the Warra SuperSite and TERN's wider ecosystem monitoring capability has greatly strengthened the way we observe how Australia's unique ecosystems respond to weather events. Tim has combined the knowledge and know-how gained from 40 years of detecting, diagnosing, and evaluating threats to forest health with the monitoring capability of the Warra SuperSite to detect and describe a previously unknown vulnerability of the tall *Eucalyptus obliqua* forest at Warra to a warming climate.

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