Summary of scientific expert feedback on the potential impact of climate change on Tasmania's production forests and potential adaptation strategies

Background report

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Disclaimers

The information presented is a broad overview of information considered relevant (by the author) to the aim of this report. Whilst the author has used her best endeavours to ensure accuracy, she does not warrant that the material is free of error. Consequently, the information is provided on the basis that the author will not be liable for any error or omission. However, should any error or omission be identified, the author will use her best endeavours to correct the information. The information in this report does not necessarily reflect the views of the FPA.

Front page photograph: Fire damage to riparian forest (Photo: D Mann)

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Executive summary

- Climate change poses a considerable challenge to forest managers, and the ways the forest industry could adapt to climate change need to be considered and be consistent with the adaptive management framework followed by the Tasmanian forest practices system.
- Information was sought from a large number of experts on the impacts of climate change, potential ways the forest practices system could adapt, knowledge gaps and factors that may inhibit uptake of adaptive measures. This report summarises the responses received.
- The FPA is an independent statutory body that administers Tasmania's forest practices system on both public and private land. Its primary responsibility is regulating the conduct of forest practices in forests and threatened non-forest vegetation. Many of the potential actions identified in this report are beyond the scope of the forest practices system and other agencies would need to lead them.
- The most recent high resolution climate projections for Tasmania were made in 2010. These climate models predict that Tasmania will warm by at least 1.5°C by 2050, and there will be an increase in extreme temperatures. It has been 15 years since Tasmania has had an annual mean temperature below the 1961–90 average, and in 2021 Tasmania's annual mean maximum temperature was 0.42 °C warmer than average and the highest since 2019 (BOM 2022). There is uncertainty in the models about the direction and magnitude of changes in rainfall, but a gradual decrease in annual rainfall is considered likely. At the same time rainfall intensity (rainfall in mm per hour) is predicted to increase as temperature rises. In 2021 Tasmania's total rainfall was 1% above the 1961–90 average, but a couple of locations experienced their highest daily rainfall on record (BOM 2022). Soil moisture is expected to gradually decrease over time. There will be a much higher frequency of hot and dry conditions in the future which reduce forest productivity and can cause large scale mortality. It is thought that by the end of the century there will be an eight-fold increase in fire risk, a longer fire season and a sharper transition from winter to summer and vice versa.
- Forests are major stores of carbon. However, the rate at which some forests accumulate carbon may decrease as temperatures increase and more fires release carbon to the atmosphere. Forest management practices are a key component for managing carbon levels in Tasmania and maintaining the health, condition and productivity of forests are key to managing forest carbon.
- Climate change is likely to impact forest health, by impacting forest regeneration, tree survival, and forest growth. However, there are several possible adaptive measures that could help maintain forest health, from improving regeneration outcomes, improving forest resilience, protecting important values, and improving the capacity of the industry to adapt and respond to change.
- A major impact of climate change is likely to be increased frequency and intensity of bushfires. The window available for doing prescribed burning, as it is currently implemented, may be narrowing. Despite these challenges there are some measures that could be adopted to reduce the incidence or intensity of fire, improve forest resilience or improve post-fire recovery. Adjusting industry expectations to changing conditions and taking extra measures to protect important values could also help manage our forests under these changing conditions.

- In terms of soil and water issues associated with climate change and more frequent fire, the more intense rainfall predicted is likely to create a higher risk of erosion. It may also result in a change to soil biota and nutrient cycling. More erosion and warmer temperatures may reduce stream health and trees are likely to experience more water stress. A range of adaptation options have been proposed, largely relating to catchment management and riparian buffers, but also to improving forest resilience to drought and fire.
- Widespread and highly variable impacts may be seen on biodiversity values under climate change, including changes in vegetation communities, shifting or loss of ecological niches, changes in the timing and efficiency of reproduction and loss of ecological function. Potential adaptation measures include improving forest resilience, reducing the intensity of forestry operations and increasing protection of important values.
- The occurrence and impact of pests and diseases may increase under a changing climate, which is likely to have a compounding impact on forest health. These impacts could be reduced by monitoring pests and diseases to detect outbreaks, monitoring responsive actions to determine effectiveness, combined with maintaining forest health to ensure forest resilience.
- While a large number of potential actions have been identified in this report, many are at risk of not being adopted because of resistance to change, lack of social acceptability or uncertainty in the effectiveness of actions, financial or logistical implications, or the current legal framework. Understanding these inhibiting factors will help determine how the forest practices system may respond effectively.
- A wide range of knowledge gaps were identified. Many respondents outlined the urgent need for more baseline monitoring data of forests and forest values. Other knowledge gaps identified were the effectiveness of various management options, climate vulnerability of various components of the forest ecosystems, long-term modelling on the impact of climate change, and more information on the factors that affect regeneration and if and how forests will burn in a wildfire.
- A summary of the potential adaptation options is provided in Table 3, including an indication of the positive and negative implications of adopting the strategy and if/how the potential adaptation option is relevant to the forest practices system.
- The impacts of climate change have implications at broad spatial scales. The forest practices system is designed to operate primarily at the operational scale through forest practices plans (typically <300 ha), but broader-scale impacts and management can be taken into account at this scale. There are also mechanisms for broader scale and catchment-level planning (through three-year planning, Vegetation Management Agreements) and associated planning tools. While broader scale impacts and management can be taken into account at the planning stage, the ability of the forest practices system to implement change at broader scales is somewhat limited.
- In conclusion, most respondents indicated that the impacts of climate change are already apparent. The most appropriate way forward is not clear as forests are complex systems, there is uncertainty around climate projections and the implications of adaptive options are not always known. The next stage of this project will be to hold a workshop with industry stakeholders to try and identify the most effective, appropriate and efficient adaptive measures for implementation through the forest practices system. These could be implemented through an adaptive management framework to maximise learnings moving forward to help ensure continual improvement.

1. Introduction

Tasmania's forest practices system is given legislative power through the *Forest Practices Act 1985*. The forest practices system recognises the many values that forests have and is designed to ensure the reasonable protection of natural and cultural values of the forest when forest practices are carried out.

The objective of Tasmania's forest practices system, as specified in Schedule 7 of the Forest Practices Act is to achieve sustainable management of crown and private forests with due care for the environment, and taking into account social, economic and environmental outcomes in a way that is as far as possible self-funding.

Forest practices regulated by the forest practices system include:

- harvesting and regenerating native forest
- harvesting and/or establishing plantations
- clearing forests for other purposes, including agriculture
- clearing and converting threatened native vegetation communities
- constructing roads and quarries for the above purposes
- harvesting tree ferns.

The Forest Practices Authority (FPA) is an independent statutory body that administers Tasmania's forest practices system on both public and private land. Its primary responsibility is regulating the conduct of forest practices in forest and threatened non-forest vegetation. Further details on the forest practices system are provided in Department of State Growth (2021).

The Tasmanian forest practices system follows an adaptive management framework which includes an emphasis on research, review and continual improvement (Wilkinson, 1999; Munks et al. 2020). The ongoing program of review and improvement of the Tasmanian forest practices system includes review of the *Forest Practices Code* in its entirety, and *ad hoc* reviews of forest management aspects associated with the Code. For example, a review of steep country harvesting was undertaken in 1991, soil and water provisions in 1997 and biodiversity provisions in the period 2007–09.

The outcome of the biodiversity provisions review was a summary document, and one of the points emphasised was the importance of considering and addressing climate change, although this fell outside the Terms of Reference given to the Review Panel (BERP, 2008). The following statement was included in the final report.

> 'Climate change is a key issue in the planning and management of biodiversity conservation and there is uncertainty about the exact nature and magnitude of future change. A landscape approach to managing forest biodiversity, modified as the panel recommends, should provide some insurance to allow biodiversity and ecological processes to respond to changing conditions' (BERP, 2008).

Other relevant comments in the report included (see Section 16 for more detail):

- 'The primary research and monitoring needs for the FPA to fulfil its charter for biodiversity conservation are to increase understanding for management in a number of areas… [including] climate change' p108.
- 'Future biodiversity planning and management should be informed by scientific understanding of likely implications of future climate change' p71.
- 'The panel notes that issues… [including] climate change… potentially impact on biodiversity in ways that are not addressed by the current *Forest Practices Code*. The panel recommends that the *Forest Practices Code* overtly and formally consider these issues for inclusion in future reviews of provisions where needed' p65.

This current review was initiated to further explore the ways in which climate change is expected to impact Tasmanian production forests and identify actions that could be taken to mitigate these impacts and key knowledge gaps. This review will help provide the context for subsequent workshops with experts and practitioners to identify effective, appropriate and efficient adaptations to forest management practices, particularly those relevant for the Tasmanian forest practices system.

2. Aim and methods

The aim of this review was to synthesise information gathered from key experts to identify:

(1) how climate change is expected to impact Tasmanian production forests (i.e. 'potential impacts')
(2) actions that could be taken to address these impacts (i.e. 'potential adaptation strategies')
(3) factors that could inhibit adoption of potential actions
(4) key knowledge gaps (i.e. 'research needs').

We identified seven key issues:

(1) carbon
(2) forest vigour and condition
(3) fire
(4) soils
(5) water
(6) biodiversity
(7) weeds and diseases.

We attempted to identify a number of experts for each of the seven key issues. Experts were identified from in-house knowledge, recommendations from others and in several instances from online searching. Tasmanian experts were prioritised in the first instance, but a number of key experts from the mainland were also approached. We did not limit the number of people approached and attempted to ensure there was no inadvertent bias in the experts approached (except for having a Tasmanian focus).

In the first instance, experts were sent an electronic letter requesting their participation and a questionnaire (Appendix 1). The option for an interview was also provided. One or two follow-up emails were sent to people who did not respond. The main forest industry companies were also approached, and a few industry employees also provided comment on the questionnaire. A total of 52 people responded (Appendix 2).

The information in this report is a synopsis of the feedback received. The information presented is a broad overview of information considered relevant (by the author) to the aim of this report and the author has tried to convey the responses concisely and objectively. To maintain privacy, each participant was allocated a number which is used (in superscript) to reference their comments. The information in this report does not necessarily reflect the views of the FPA. Many of the suggestions received fall outside the jurisdiction of the FPA (as indicated in Table 2) but have been included for completeness to inform stakeholders in the forestry sector and to encourage them to consider what contributions they could make to mitigate the effects of climate change.

A full review of the published literature relevant to the subject of this report was not conducted and the information provided in this report is largely not referenced by scientific literature. While most of the ideas presented are supported by science, mostly published, the process undertaken (contacting researchers directly) meant it would be time consuming to fully reference the document and the decision was made to not to fully reference the material presented. However, a reading list is included at the end of this document which should provide references for most of the ideas presented. Some respondents provided supporting references and these are included in this report.

3. Policy and legislative context

3.1. Federal policy and legislation

The following is a very brief overview of the legislation relevant to both climate change and forestry in Australia and Tasmania.

3.1.1. *Climate Change Authority Act 2011*

This Act establishes the Climate Change Authority. The Authority is to conduct reviews under the *Clean Energy Act 2011*; the *Carbon Credits (Carbon Farming Initiative) Act 2011*; and the *National Greenhouse and Energy Reporting Act 2007*. It also establishes the Land Sector Carbon and Biodiversity Board which is to advise the Environment Minister, the Climate Change Minister and the Agriculture Minister about climate change measures that relate to the land sector.

3.1.2. National Climate Resilience and Adaptation Strategy 2021–25

On 29 October 2021, the Australian Government released a revised *National Climate Resilience and Adaptation Strategy*. The Strategy sets out what the Australian Government will do to support efforts across all levels of government, business and the community, to better anticipate, manage and adapt to the impacts of climate change. It identifies a set of principles to guide effective adaptation practice and resilience building and outlines the government's vision for the future.

The guiding principles are

1. shared responsibility
2. factor climate risk into decisions
3. assist the vulnerable
4. evidence-based, risk management approach
5. collaborative, values-based choices
6. revisit decisions and outcomes over time.

This is a high-level document that makes no mention of forestry other than to acknowledge foresters as one of a number of land stewards the government is committed to support.

3.1.3. *Clean Energy Regulator Act 2011*

This Act establishes the Clean Energy Regulator, which has functions conferred on it by or under the *Carbon Credits (Carbon Farming Initiative) Act 2011*, the *National Greenhouse and Energy Reporting Act 2007*, the *Renewable Energy (Electricity) Act 2000* and the *Australian National Registry of Emissions Units Act 2011*.

The Clean Energy Regulator is an independent statutory authority responsible for administering legislation that will reduce carbon emissions and increase the use of clean energy. The responsibilities of the Clean Energy Regulator include:

- providing education and information on the schemes they administer
- monitoring, facilitating and enforcing compliance with each scheme
- collecting, analysing, assessing, providing and publishing information and data
- accrediting auditors for the schemes they administer
- working with other law enforcement and regulatory bodies.

The National Greenhouse and Energy Reporting scheme provides a national framework for reporting and disseminating company information about greenhouse emissions, and energy production and consumption. This informs policy and program development nationally and reporting internationally.

The Emissions Reduction Fund aims to help reduce Australia's emissions by providing an incentive for businesses, landowners, state and local governments, community organisations and individuals to adopt new practices and technologies which reduce emissions. The Plantation Forestry Method provides opportunities for the plantation forestry industry to participate in the Emissions Reduction Fund (Clean Energy Regulator 2022). Under the 2022 revision plantations at risk of returning to non-forest as well as plantations being transitioned to permanent forest can be considered.

The Renewable Energy Target encourages investment in new large-scale renewable power stations and the installation of new small-scale systems, such as solar photovoltaic and hot water systems in households. The Renewable Energy Target is designed to reduce emissions of greenhouse gases in the electricity sector and encourage the additional generation of electricity from sustainable and renewable sources.

The Australian National Registry of Emissions Units is a secure electronic system designed to accurately track the location and ownership of Australian carbon credit units and emission units issued under the Kyoto Protocol.

3.2. Tasmanian policy and legislation

3.2.1. *Climate Change (State Action) Act 2008*

The *Climate Change (State Action) Act 2008* provides the state's legislative framework for action on climate change and includes a requirement that an independent review of it be undertaken every four years. The most recent independent review of this Act was completed in 2021.

The *Climate Change (State Action) Amendment Bill 2021* (Amendment Bill) was developed in response to the most recent independent review of this Act and was tabled in the House of Assembly on 24 November 2021. It is expected the Amendment Bill will be debated in Parliament in the second half of 2022. The Amendment Bill establishes a whole-of-economy emissions reduction target of net zero emissions, or lower, from 2030 to provide a flexible approach to emissions reduction, in recognition that sectors have different opportunities to reduce their emissions, and some will require more time, support and technology advancements to transition to a low emissions future. The Amendment Bill establishes a legislative requirement for a state-wide climate change risk assessment to be completed every five years.

The Amendment Bill also prescribes that sectoral Emissions Reduction and Resilience Plans will be developed, in partnership with industry, to ensure a practical and balanced approach is taken to sector-based emissions reductions and adaptation. The Amendment Bill requires an Emissions Reduction and Resilience Plan to be developed for Tasmania's Land Use, Land Use Change and Forestry sector.

3.2.2. Climate Change (Greenhouse Gas Emissions) Regulations 2012

These Regulations facilitate the measuring and reporting of greenhouse gas emissions.

3.2.3. Tasmania's Climate Change Action Plan 2017–21

Tasmania's Climate Change Action Plan is out of date, and a new plan is due for release in late 2022. However the expired Action Plan provides useful background context for climate change action in Tasmania. It is structured into six priorities, each of which has a 2021 vision statement.

1. Understanding Tasmania's future climate: commits to providing up-to-date information on climate change projections and impacts, and tailoring this information to support decision making across key industry sectors.
2. Advancing our renewable energy capability: supports national energy security solutions in the transition to a low carbon generation network and delivers energy efficiency programs with local government, households and businesses.

3. Reducing our transport emissions: promotes the uptake of electric vehicles and other alternative forms of transport, and optimises the use of vehicles to reduce costs and emissions.
4. Growing a climate-ready economy: supports businesses and agricultural producers to reduce their emissions, be prepared for the impacts of climate change, and leverage opportunities.
5. Building climate resilience: enhances our capacity to withstand and recover from extreme weather events, and better understand and manage the risks of a changing climate.
6. Supporting community action: establishes an aspirational emissions reduction target of zero net emissions by 2050, recognises that all Tasmanians have a role to play in tackling climate change, and assists the community to reduce emissions and energy use.

3.2.4. Tasmanian Regional Forestry Hub

The Hub exists to provide information to assist the Commonwealth in future policy development regarding pathways for growth, and removal of barriers, for the forestry industry through stakeholder engagement and consultation.

The forest industry and community have identified through the Hub, that to achieve the objectives outlined in the Commonwealth's *National Forest Industries Plan* (National Plan), and the Tasmanian Forest Industry Ministerial Advisory Committee's *Strategic Growth Plan*, a long-term vision addressing the sector's strategic priorities and enablers is required.

A Road Map has been developed to focus on the key message from the National Plan, 'A billion more plantation trees – the right trees at the right scale in the right places.' The Hub's strategic priorities and key activities have been developed with a view to enabling Tasmania to contribute towards this national goal, and to fostering an innovative forestry industry.

The Hub's vision is supported by four key strategic priorities outlined below which will inform the Road Map:

1. climate and carbon policy
2. workforce skills and training
3. resource and land access
4. supply chain and infrastructure.

A priority for the Hub is for active and adaptive forest management to be a key driver of positive climate outcomes in Tasmania and Australia. This is in recognition that international climate experts, including the International Panel for Climate Change (IPCC) and the Food and Agricultural Organisation (FAO), have identified that active forest management plays a critical role in carbon pollution reduction strategies.

The following climate and carbon policy enablers have been identified in the Tasmania Regional Forestry Hub Road Map 2021.

Regulatory changes

- Development of a Commonwealth procurement policy that recognises the full life cycle impacts of forest building products, not just those products in use.
- Enactment of the King Review recommendations encouraging greater participation in the Emissions Reduction Fund (ERF).
- Enactment of the proposals in the Clean Energy Regulator's consultation paper on proposed changes to the audit framework to streamline audit requirements.
- Streamlining the regulatory approval process for prospective forest carbon projects in southern Tasmania under the '600 mm rainfall rule'.
- Streamlining the Plantation Forestry methodology. This includes encouraging conversion from short to long rotation plantations and simplifying the process, particularly for growers of small to medium-sized estates.

Natural capital accounting

- Encouraging industry implementation of natural capital accounting systems to demonstrate scale benefits and to enable environmental reporting at scale.

Alternate species

- Testing and assessment of alternative tree species or varieties that are potentially better suited to future climate conditions.

3.3. Other

- In response to the 2016 bushfires, the Tasmanian Government delivered the $250,000 Tasmanian Wilderness World Heritage Area (TWWHA) Bushfire and Climate Change Research Project to investigate the impact of climate change on bushfire risks to the TWWHA, and recommend ways to improve how Tasmania prepares for and responds to bushfires in the TWWHA. The Research Project confirmed the TWWHA is likely to experience increasing bushfire risk as a result of a changing climate, and that the conditions that led to the 2016 bushfires (including vegetation dryness, soil dryness and flammability, and increased frequency of dry lightning strikes) are expected to become more frequent as the century progresses[33].
- In 2020, the Tasmanian Government commissioned Point Advisory and Indufor to deliver Tasmania's Emissions Pathway Review (TEPR), to model Tasmania's future emissions pathways to 2050, and identify options to amend Tasmania's emissions reduction target. The report proposes a net zero emissions target for 2030 and outlines some emission reduction opportunities available to Tasmania (Point Advisory, 2021). The net zero target relies upon carbon sequestration by Tasmanian forests, but our understanding of how forests will sequester carbon under climate change is still evolving (Section 5.1.1). The forestry sector is acknowledged as having a key role to play in meeting carbon emission targets. In accordance with international accounting rules, a smoothing function is applied to natural disturbances such as fire which will underestimate true carbon emissions in the year of a wildfire(s) that is subject to the natural disturbance provision, and overestimate true carbon emissions when there are no natural disturbances that trigger the natural disturbance provision (Section 5.1.1).
- The preliminary findings of TEPR reveal that the Land Use, Land Use Change and Forestry sector plays the most significant role in Tasmania's current and future emissions

profile and highlights the important role of Tasmania's production forests in maintaining Tasmania's net zero emissions status[33].

- TEPR identified a number of emissions reduction opportunities available to the Tasmanian Government across all sectors of the economy[33]. In relation to the forestry sector these include:
  - reducing conversion of plantations to other land uses
  - increasing plantations including agroforestry
  - increasing proportion of forestry logs directed to long term wood products and increased domestic processing
  - introducing measures to reduce the risk of major bushfires.

3.4. Forest practices system

Table 1. A summary of current references to climate change in the *Forest Practices Code 2020*.

Code Section	Code provision
A1.1 Context – Forest Carbon and climate change (P3)	Forest practices should be conducted in a manner that maintains the sequestration and storage of carbon in a reasonably practical manner by: • avoiding unnecessary damage to forest growing stock and soils • maintaining site productivity • ensuring the prompt reforestation and growth of forests after harvesting. Forest practices should ensure that native forests are regenerated using seed from local or similar provenances in a manner that contributes to the maintenance of genetic diversity, taking into account the potential of ecosystems and species to adapt to climate change.
E.1 Reforestation and forest establishment – General Principles (P76)	The aim of establishing native forest regeneration should be to maintain the forest type, i.e. forest structure and species composition, unless specific management objectives such as enhancing habitat for fauna or adaptation to climate change are stated in the FPP.
E1.4 Species selection – General Principles (P83)	Seed or seedlings should be of species suited to the soil and climate of the area to be reforested. Forest practices will ensure that harvested native forest is regenerated using seed from local or similar provenances and in a manner that helps maintain genetic diversity. Species selection should consider the potential effects of climate change.
E1.4 Operational approach – Native forest (P83)	Other species should not be used or added to the sowing mix, except for control of forest diseases or for climate change considerations and following expert advice. For example, when a site at high risk of damage from *Phytophthora cinnamomi* (root-rot fungus) is being sown with eucalypts, a significant portion of the seed should be from *Phytophthora cinnamomi*-tolerant species, such as *Eucalyptus globulus* and *E. viminalis.* Background information can be found in FPA's Flora Technical Note 8: Management of *Phytophthora cinnamomi* in production forest (8).
E1.4 Operational approach – Plantations (P83)	Species and provenances should be selected which are suitable for the site and climate, and are likely to provide sustainable growth rates.

4. Climate projections for Tasmania

[The information below has been provided by the Climate Futures programme at the University of Tasmania].

Tasmania is a highly variable landscape, ranging from cool-temperate to alpine climates across the state. Due to this spatial heterogeneity, Tasmania needs higher resolution information than is available from global circulation models (Corney et al. 2010). The most recently published assessments of climate-change impacts on the Tasmanian state were conducted through the Climate Futures for Tasmania project (CFT), completed around 2010

(Bennet et al. 2010,Grose et al. 2010, Holz et al. 2010, McInnes et al. 2011, White et al. 2010).

The Climate Futures for Tasmania project is the most important source of climate change projections for Tasmania. These projections indicate that by 2100, under a high emissions scenario, Tasmania can expect:

- a significant change in rainfall patterns from season to season and varying between different regions[33]
- a rise in annual average temperatures by up to 2.9°C by 2100, including more hot summer days, more heat waves, and substantially reduced incidence of frost and snow[33]
- longer fire seasons and more days at the highest range of fire danger
- an increase in the number of storms[33].

These projections are generally consistent with the more recent tailored climate change projections for Tasmania prepared in 2016 by CSIRO and the Bureau of Meteorology through its Climate Change in Australia project[33].

As current climate projections are 12 years old, there is a need for them to be updated. Recently (August 2022) the Queensland Government has completed 10 km resolution projections over the entire Australian continent. These data could underpin an updated impact analysis. Further, the Tasmanian government is currently reviewing the climate data and services needs of government and private enterprise. Convection permitting regional projections have been identified as a potential area that can add value, although any commitment to funding this activity is yet to be considered or announced. These would not be available until 2024 at the earliest if selected as an area of investment. Updating the projections with convection permitting resolutions (~2 km^2) is critical because observations are indicating that Tasmania's climate is tracking the more extreme projections. For example, high intensity rainfall on the East Coast has been higher than projected by either Australian Rainfall and Runoff climate change guidance, or reports within the Climate Futures for Tasmania projections.

4.1. Temperature

All assessments agree that compared to Tasmania's historical climate, a warming of at least 1.5°C by 2050 is projected (even following low-emissions scenarios) (Grose et al. 2010; Love et al. 2017; Love et al. 2019; Remenyi et al. 2020; Remenyi in-prep). Following a lower emissions scenario (with dramatic reductions from about 2020 onwards), stabilising global climate below 2°C is possible. However, all other scenarios warm more than this (particularly at higher elevations although this may be mediated to some extent by wind[51]), with the strongest warming trends produced by CMIP5 models following a 'business-as-usual' RCP8.5 scenario, with warming of about 3°C across the state (and >4°C in the alpine regions) (Grose et al. 2010; Love et al. 2017; Love et al. 2019; Remenyi et al. 2020; Remenyi in-prep). Minimum temperature averages and extreme high temperatures rise in all locations, which is particularly important where this means a reduction in the frequency of snow or the thickness of snow on the ground (Love et al. 2017; Love et al. 2019; Remenyi et al. 2020). Cold spells are projected to decrease (ACE CRC 2010).

Evidence of warming is already being seen. It has been 15 years since Tasmania has had an annual mean temperature below the 1961–90 average, and in 2021 Tasmania's annual mean maximum temperature was 0.42 °C warmer than average and the highest since 2019 (BOM 2022).

4.1.1. Extreme temperature

All assessments on the land or in the ocean indicate an increase in all types of high temperature extremes, be they specific biologically relevant thresholds, maximum daily temperatures or heatwave intensity and frequency (more than 50 papers since 2010, good examples being Fox-Hughes et al. 2014; Porfirio et al. 2016; Harris et al. 2018; Remenyi et al. 2020). Hot conditions can lead to conditions also becoming drier, and the combination of hot and dry can be especially challenging for forests (Mitchell et al. 2014).

4.2. Annual rainfall

There is far less agreement in model outputs about the direction or magnitude of change for rainfall (Bennet et al. 2010; Grose et al. 2010; Remenyi et al. 2020; Remenyi in-prep). CMIP3 results suggest a change in the seasonality of rainfall, more in summer/autumn, less in winter/spring, but minimal change annually (Bennet et al. 2010; Grose et al. 2010). However, this assessment was based on 'wetter models' from the CMIP3 archive which suggest 'minimal change' in rainfall is a best-case scenario. Subsequently, CMIP5 analyses, based on a selection of models that better sample the plausibility space (i.e. some wet, some dry and some moderate) has found that wetter models are in the minority of projections (Grose et al. 2010; Grose et al. 2016) and require very specific conditions. A gradual decrease in annual rainfall over Tasmania is far more likely as the frequency of westerly, rain-bearing fronts decreases (Remenyi et al. 2020; Remenyi et al. in-prep), and there is mounting evidence that high elevation regions across the state (i.e. >800m) will be drier in response to a warming climate (Grose et al. 2019).

4.2.1. Extreme rainfall

As atmospheric temperatures rise, rainfall intensity increases (rainfall in mm per hour). However, a larger driver of rainfall intensity is a synoptic system that produces much of the rainfall in eastern Tasmania: east-coast lows. These typically produce damaging, highest intensity rainfalls (Pook et al. 2010) on the east coast (occasionally into the Midlands). In the models predicting a wetter climate, an increase in the frequency of east-coast lows means annual rainfall levels remain relatively constant, but the rainfall is more intense and episodic, particularly in the east and south-east regions (Bennet et al. 2010; Grose et al. 2010; Remenyi et al. in-prep). In the 'drier' models, there is also an increase in the frequency of east-coast lows, although not as large an increase as in the 'wetter' models (Remenyi et al. in-prep). The west coast is likely to experience lower rainfall, particularly in summer, and the risk of flooding is likely to increase in the west and north-east coastal regions with longer dry periods between rain events (ACE CRC 2010).

In 2021 Tasmania's total rainfall was 1% above the 1961–90 average, but a couple of locations experienced their highest daily rainfall on record (BOM 2022).

4.2.2. Soil moisture

All assessments project a gradual decrease in soil moisture (as measured by the Soil Dryness Index) into the future (Fox-Hughes et al. 2015; Love et al. 2017; Harris et al. 2018; Love et al. 2019; Remenyi et al. 2020). This is driven primarily by evaporation in 'wetter' models, and by a combination of evaporation and reduced rainfall in 'moderate' and 'dry' models. The largest absolute changes are in the wettest regions (where there is more water to evaporate), whereas the largest percentage changes are in the drier regions (where small volumes mean smaller changes result in larger percentages). Even where the annual rainfall is predicted to be similar, the less frequent and more intense pattern of rainfall means it will not have the have same impact on soil moisture. Increased demand for irrigation water will also reduce water available at particular locations[6].

4.2.3. Stream flow

Changes in streamflow are expected, including changes to peak flows (i.e. potentially more and greater flooding) and more frequent and longer periods of low flow in unmodified streams[6]. In modified streams, the hydrological regimes will change as water managers respond to the changing demands on water and the changes to the water resource[6]. These changes are harder to predict and will be particular to the circumstances of a given location[6].

4.3. Fire danger

Across Tasmania there are many landscapes, with differing key fire weather variables or metrics (Love et al. 2017, 2019). In all cases, the drying of the landscape is increasing the risk of future fires.

Daily values of McArthur Forest Fire Danger Index were generated at 10-km resolution over Tasmania, Australia, from six dynamically downscaled CMIP3 climate models for 1961–2100, using a high emissions scenario (Fox-Hughes et al. 2015). Model projections showed a broad increase in fire danger across Tasmania, but the increase was smaller in western Tasmania (district mean cumulative fire danger increasing at 1.07 per year) compared with parts of the east (1.79 per year) (Fox-Hughes et al. 2015). There was noticeable seasonal variation, with little change occurring in autumn but a steady increase in area subject to springtime 99th percentile fire danger (Fox-Hughes et al. 2015). Days of elevated fire danger based on sea level pressure patterns increased in frequency during the simulated twenty-first century: in south-east Tasmania, for example, the number of such events detected rose from 101 (across all models) in 1961–1980 to 169 by 2081–2100 (Fox-Hughes et al. 2015).

All metrics indicate a lengthening of the fire season, with sharper transitions from winter to summer and vice versa (Fox-Hughes et al. 2015; Love et al. 2017; Harris et al. 2018; Love et al. 2019). This means the length of the prescribed burning season (late spring/early autumn) is projected to be reduced. Although there may be an increase in the potential for management in the historically wetter period, reduced daylight hours over this period makes it a challenging time for fire managers to operate productively in the field. In areas dominated by native vegetation, some areas are projected to become so dry that they will be experience a risk from fire for the first time in thousands of years (Love et al. 2017; Harris et al. 2018; Love et al. 2019). Risks to human settlements such as towns, suburbs and cities are also increasing, either directly from a drier landscape, more prone to ignite, or due to smoke being transported into settlements from fires burning in remote areas (Marfori et al. 2020).

4.4. Sea level rise

Sea level rise was one of the first climate change impacts with international consensus about the direction of change, with strong agreement across a suite of models for the rate of sea level rise by the end of century. Around Tasmania, sea level is expected to rise by 0.8–1.0 m by the end of century (McInnes et al. 2016), which will affect low-lying regions.

4.5. Wind

Modelling of regional wind hazard across Tasmania, based on a high emissions and low emissions scenario, found modest increases in wind hazard projected by 2100 (ACE CRC 2010). However, there are regional differences, with high hazard regions including Bass Strait islands and elevated areas (particularly in the northeast), and low hazard in major valley regions such as the Derwent and Tamar valleys (ACE CRC 2010). A model of wind risk for Hobart was produced (Cechet et al. 2012). The model predicted that the strength and frequency of strong wind gusts is expected to reduce under a changing climate, because the stronger wind systems are likely to move further south[24].

5. Carbon

The *Forest Practices Code* (2020, p3) states the following in relation to forest carbon and climate change:

- Forest practices should be conducted in a manner that maintains the sequestration and storage of carbon in a reasonably practical manner by:
    - avoiding unnecessary damage to forest growing stock and soils
    - maintaining site productivity
    - ensuring the prompt reforestation and growth of forests after harvesting.

A strategic assessment of how climate change and Australia’s carbon policy impacts upon Tasmania’s forestry sector, with an assessment of opportunities and barriers, was done by Keenan et al. (2020). ‘Forests are an important component of the global carbon cycle. Maintaining, expanding and better managing forests, and using more forest products, have the potential to contribute to national and international objectives to reduce greenhouse gas emissions’ (Keenan et al. 2020).

5.1. Potential impacts

5.1.1. Reduced storage of carbon in forests

Fire reduces carbon stocks in forests

Current Paris and UNFCC reporting put Tasmania as carbon negative, yet clearly there are emissions from fossil fuels from a number of sources (e.g. in vehicle engines and stationary energy sources that provide heat or electricity or both to industrial applications or buildings that burn fossil fuels such as LNG, LPG and diesel). The emissions from these sources are offset by the sequestration of carbon in our forests.

Fires in Tasmanian forests, whether wildfire or planned, release carbon into the atmosphere. Wildfire (and some planned burns) also affect forest carbon by influencing forest mortality and regrowth (Fairman et al. 2022). In terms of national greenhouse gas accounting, the accepted way of accounting for natural disturbances such as wildfire over a certain size is that burnt areas are excluded from the carbon accounts for five years and returned after this period[52]. This is because the international standard is to apply a smoothing function to natural disturbance (DISER, 2020) to ensure that emissions and subsequent removals from non-anthropogenic natural disturbances average out over time (IPCC, 2006). Australia has a requirement to align with international accounting rules. This approach results in an annual underestimate of true carbon emissions in the year of a wildfire(s) that is subject to the natural disturbance provision, and an overestimate of true carbon emissions when there are no natural disturbances that trigger the natural disturbance provision.

A study done in fire-tolerant forests in south-eastern Australia compared the impacts of one and two (six-year interval) high-severity wildfires on carbon stocks two to three years after the last wildfire (Fairman et al. 2022). Aboveground carbon stocks in live biomass and soil carbon stocks to 10 cm depth decreased significantly with each wildfire (Fairman et al. 2022). The authors suggest that the potential for carbon stock recovery could be ‘compromised by predicted warmer and drier (i.e. more arid) future climates, and by soil feedbacks to productivity’ (Fairman et al. 2022). Other studies have also raised concern that Australian forests may store less carbon under climate change, particularly as wildfires occur in more rapid succession (Bowman et al. 2020). There is a risk that the impact of fire on carbon could be a relatively rapid step-change, with repeat fires burning through regrowth too young to self-regenerate[25], although some respondents think fuel hazard reduction burning will reduce the risk of this[51]. However, simulation studies of fire-carbon dynamics in *Eucalyptus* temperate forests in the NSW high country suggest that increased suppression or prescribed burning is likely to be insufficient to counteract carbon losses from increasingly frequent fires associated with climate change (King et al. 2011, cited by Bowman et al. 2020).

Young forests regenerating from clearfelling may be more likely to experience high severity fires than unlogged conditions when not under extreme fire weather (Bradstock et al., 2012, Bowman et al. 2020), but carbon losses following high severity fire in regrowth forests are lower than from mature forests (Bowman et al. 2020).

Soil carbon constitutes 30–50% of total ecosystem carbon in Tasmanian forests (McIntosh et al. 2020). No statistically rigorous studies have been done on the effects of fire on soil carbon: the results of Slijepcevic (2001) and Pennington et al. (2001) at Warra were somewhat contradictory and inconclusive. However, frequent fires are likely to have caused the marked difference of soil type and soil carbon between wet eucalypt forests and dry eucalypt forests – the latter have texture-contrast soils and lower carbon content and lower fertility, probably induced by the more frequent fires in the dry forest types (McIntosh et al. 2005). These authors noted that 'Fire depletes nutrients in forests by causing losses to the atmosphere, losses by runoff, and losses by leaching. Nutrient loss by fire encourages fire-tolerant vegetation adapted to lower soil nutrient status, so frequent fire is a feedback mechanism that causes progressive soil nutrient depletion.' In the context of this report, it should be remarked that the feedback mechanism will also serve to lower soil carbon by destroying organic matter, diminishing organic matter supply to the soil, inhibiting clay–organic matter linkages and soil faunal mixing, and promoting clay eluviation. Thus it is likely that increasing frequency of fires will promote forest vegetation types more adapted to frequent fires and lower soil carbon levels, i.e. the shift from wet forest to dry forests.

Carbon uptake by forests decreases during heatwaves

More heatwaves will potentially cause long-term loss of carbon stocks in native forests and in plantations (Wen et al. 2006, Norris et al. 2012) [35]. Recent evidence from the Warra Flux tower site in southern Tasmania found tall *Eucalyptus obliqua* forest suffered a sharp decline in productivity during the record-breaking heatwave of November 2017, with the forest switching from being a strong carbon sink to a carbon source. The decline in productivity was associated with a sharp reduction in gross primary productivity, a small increase in respiration and a sharp increase in latent heat flux[35]. This work also found that between 2013 and 2015 carbon uptake in the forest declined during summer months as temperature increased[33]. This has implications for the long-term permanence of carbon stored in native forests in Tasmania[33, 35]. This change in forest respiration in response to temperature provides a potentially large positive feedback to global warming that is not captured in the widely-used carbon accounting model (FullCAM). The 3PG module that predicts growth in FullCAM does not have any dependencies based on high temperature, only freezing temperatures and low water availability (Landsberg and Waring 1997)[43].

Rates of carbon sequestration can also decline if plants are respiring more, or trees are dying. There is some evidence that plants are reducing their ability to photosynthesise under extreme heat so carbon sequestration may be low in drier forest types also[12]. There is also evidence showing that forest mortality is occurring due to vascular failure at high temperatures (Bauman et al. 2022, Brodribb et al. 2020).

5.1.2. Changes to how the industry operates

Carbon is becoming a valued commodity under climate change, by the community and the industry. Management of forests for carbon specifically may change some components of how the industry operates moving forward.

There may be increased demand for forest reservation

As forests store carbon, there may be increased pressure to reserve forests to offset fossil emissions[29]. With more active fire in the landscape, fire-intolerant species will be placed at greater risk and forest age is likely to decrease, making old-growth more valuable from a biodiversity, social perspective and in some communities a carbon perspective. Iconic high-carbon-density forests, and fire intolerant rainforests are likely to receive more attention as they become rarer and knowledge of the threat increases[29]. However there is some debate about whether carbon storage may actually reduce as some forests age and transition into a different successional stage[50,51].

There may be increased demand for 'climate smart forestry'

'Climate smart forestry' is 'a targeted approach or strategy to increase the climate benefits from forests and the forest sector, in a way that creates synergies with other needs related to forests' (Nabuurs et al. 2018). The approach acknowledges the important role that forests play in the carbon cycle and the role that active forest management can plan in regulating, mitigating and adapting to climate change impacts. There are three key components of climate smart forestry.

- increase the forest area and avoid deforestation to mitigate climate change by reducing and/or removing greenhouse gas emissions
- adapt forest management to build resilient and productive forests
- use wood for products that store carbon and substitute emission-intensive fossil and non-renewable products and materials (Nabuurs et al. 2018, Verkerk et al. 2020).

To implement climate smart forestry requires a policy setting that finds an appropriate balance between short and long-term goals, as well as carbon management with the other values provided by forests (e.g. biodiversity, ecosystem services) (Verkerk et al. 20020).

Carbon mitigation measures may lead to increased demand for wood products

It may be that there is an increased demand for and use of wood products as a low carbon resource to reduce fossil fuel emissions and for the carbon sequestration benefits of managing forests (Ximenes et al. 2016). This may increase pressure on managed forests to produce wood, including increasing the managed forest area (afforestation/reforestation) [29].

There may be increased pressure to actively manage and report on carbon

Increased pressure to report on forest carbon stocks and fluxes to demonstrate good forest stewardship is already beginning to occur [29]. FSC (Forest Stewardship Council) and PEFC (Programme for the Endorsement of Forest Certification) already have carbon related requirements, and ASNZS 4708 (Australian/New Zealand Standard) requires forest managers to minimise emissions, consider the impact of climate change on forests and forest management, and maintain the capacity to store and sequester carbon[34]. A balance will need to be found between managing carbon and managing other forest values[29], which may require carbon sequestration taking precedence[51].

5.2. Potential adaptation strategies

5.2.1. Increase forest resilience

Forest resilience is the ability of a forest to absorb disturbances and re-organize under change to maintain similar functioning and structure (Scheffer 2009, from Reyer et al. 2015).

Vary the genetic stock of the seed sown

Some researchers think that our forests may not be currently adapted for contemporary and future conditions, but to past conditions under which species evolved[12]. Varying the species or genetic stock to have more plants adapted to current and future conditions should increase carbon sequestration rates.

Sow more seed

Sowing a greater amount of seed should facilitate natural selection for the climatic conditions experienced at the time. This should increase the probability of genotypes better adapted to current conditions to grow, which will help improve rates of carbon sequestration[12]. However dense, tall regenerating stands may have implications for other factors such as moisture availability[46].

Take measures to reduce risk of bushfire

Bushfires introduce large pulses of carbon into the atmosphere. Under climate change there is a greater risk of more intense and more frequent wildfire (see Section 7). Introducing measures to reduce the risk of major bushfires (some of which are outlined in Section 7.2) should minimise Tasmania's emissions.

Maintain or increase structural diversity of forests

Aponte et al. (2019) found structural diversity to be a good predictor of carbon storage in forests in south-east Australia. Community weighted mean of maximum tree height and standing tree wood density were also good predictors. Therefore, maintaining diverse and structurally complex forests should help maximise carbon storage.

5.2.2. Reduce carbon footprint of forestry

Modified harvest rotations

Different rotation lengths are likely to be required for long-term storage of carbon, or for maximising carbon capture[12]. Shorter rotations should result in higher genetic turnover and may promote adaptation to current climatic conditions to help maintain carbon uptake[12]. However, there are likely to be some perverse outcomes for biodiversity and potentially fire, production and carbon (log size will be smaller under shorter rotations which limits opportunities to produce products with low-embodied energy, i.e. sawn timber, that contribute to long-term storage of carbon).

Increasing the rotation interval in planted forests is seen by some respondents as an important way that the forest industry could increase carbon sequestration (Keenan et al. 2020), and the

Emission Reduction Fund's (ERF) Plantation Forestry Method is currently incentivising the conversion of short rotations to long rotations. A long rotation plantation will store more carbon in the trees as they are growing (trees grow to a bigger size and are in the ground longer) and also the proportion of the timber products eventually produced from a long rotation plantation (predominantly sawlogs producing long lived timber framing, furniture other sawn products) will store carbon longer after harvesting that short rotation crops which are predominantly pulped for short lived paper and other pulp products, hence the enhanced carbon outcomes[53]. The ERF calculates the baseline carbon outcome from short rotation (low) and the project carbon outcome from a long rotation (higher) and then credits the difference through the payment of Australian carbon credit units (ACCUs)[53].

Eliminate post-harvest burns

Ceasing post-harvest burns would reduce carbon emissions per forestry operation[3] but would result in less effective regeneration (e.g. reduced tree density) with associated negative consequences (e.g. for carbon sequestration). However, there may be alternatives which would help reduce the carbon footprint of forestry, such as lower intensity burns, mechanical disturbance or seedbed creation[34].

Reduced use of fossil fuels

The industry needs to reduce its use of fossil fuels, as this is one of the industry's biggest emissions[25]. This could include greater use of electric vehicles and machinery, increasing use of biofuels and include greater on-shore processing of forest products.

5.2.3. Maintain or enhance forest cover

Minimise deforestation

Forests capture and store carbon, so forests are a critical component of carbon accounting. Converting forest to other land uses therefore increases Tasmania's carbon footprint in the short and long term. Furthermore, converting a forest to agricultural land use increases Tasmania's carbon footprint as agriculture has a significantly greater carbon output than a forest, thereby compounding the negative impact of clearing the forest.

Maintaining and potentially expanding Tasmania's forest estate was identified as a way to reduce greenhouse gas emissions in Tasmania's Emissions Pathway Review[33]. Levels of native forest conversion are low but ongoing on private land (there was a 22,000 ha or 0.7% reduction between 2011 and 2017, FPA 2017). Conversion of plantations to agriculture is relatively high (there was a 12,000 ha or 3.9% reduction between 2011 and 2017, FPA 2017). It has been proposed that a method for accounting for carbon gains by avoided deforestation may reduce land clearance (Keenan et al. 2020).

Plant more trees

One of the key strategies often identified for managing carbon budgets is to plant more trees, which will capture carbon as they grow (Keenan et al. 2020)[34]. Planting on fertile, productive sites is more likely to result in successful plantations and greater carbon sequestration under a changing climate (Keenan et al. 2020)[51].

The Australian Government launched the National Forest Industries Plan: *Growing a Better Australia – A Billion Trees for Jobs and Growth* in September 2018. Amongst other initiatives, the Plan aimed to establish a billion new trees over the next decade (including 400,000 hectares of new plantations nationally) in order to meet a projected four-fold increase in global and domestic wood fibre demand by 2050. The potential for additional large scale industrial plantation establishment in Tasmania is very limited. A recent assessment report by the Tasmanian Regional Forestry Hub found there was at most 37,000 ha of land suitable and available for industrial scale plantation establishment in the north of the state (total plantations in Tasmania currently occupy approximately 280,000 ha) (Greenwood Strategy 2020). Other commercial, social and environmental constraints would likely limit this figure even further[53]. The Hub report highlighted the only feasible means of getting more trees in the ground is to better integrate tree planting and forestry onto farms in ways which recognise that small, independent landowners have a range of motivations for considering tree plantations (Greenwood Strategy 2020). The challenge remains to demonstrate trees have multiple co-benefits and can be a viable and productive activity alongside farmers other agricultural enterprises[53].

5.2.4. Active management of carbon

Landscape management and climate smart forestry

Greater consideration of carbon management at a landscape scale would improve carbon capture and storage in Tasmania. Some respondents argued that optimal carbon management would be achieved by ceasing native forest logging[51], while most argued that production forestry had an important role to play in carbon management. Landscape consideration of carbon could be achieved by incorporating the principles of ‘climate smart forestry’ into current land management[52].

Changes to landscape management might include identifying high carbon forests that will not provide enough benefit to harvest and putting these in retained areas[29]. It may involve reconsidering current management boundaries (i.e. reserved and production areas) to plan for future high carbon forests given the dynamic nature of Tasmanian forests[29]. For example, consideration could be given to harvesting younger post-fire forests in the reserve system and not harvesting older forests currently in the production estate[29]. The trade-offs that would be considered when making these landscape-scale decisions would need to be considered carefully in light of the multiple values provided by the forests[29].

Improve carbon accounting

Carbon accounting needs to improve to more closely reflect the true capture and emission of carbon in Tasmania. This should differentiate between fossil carbon emissions and biogenic carbon emissions[29], cover the variable role forests have in carbon capture and emission[43] and the interaction between forestry, fuel loads and bushfire risk[3].

In accordance with agreed international conventions, the Australian Government has established natural disturbance provisions to place an upper limit (or cap) on the impact of bushfires on the national greenhouse gas inventory. This effectively means that Australian jurisdictions can exclude the impact of major fires on annual greenhouse gas accounts, provided the area burned is restored over an allocated period – and if not, the land use conversion and associated emissions are then recorded in the inventory[33]. However, all emissions from major bushfires will have a direct emissions impact on the atmosphere and contribute to climate change in this way, and therefore should be properly taken into account[33].

It will be important to develop user-friendly systems for predicting carbon gains and losses from different land and forest management systems (including plant to product carbon calculations) as an indicator of sustainability of different forestry operations[44]. For plantation forests these models are relatively well developed, however for native forests the wide variety of forest types and the array of silvicultural regimes and management activities that are undertaken mean there is high variability in the carbon responses of these forests to management interventions[53]. To this end the FPA has developed a statistically rigorous sampling procedure which is able to detect significant differences in soil carbon concentrations between different forest land uses (McIntosh et al. 2022). Such sampling procedures could be used to provide dependable baseline data potentially useful for detecting soil trends under a changing climate.

Improve carbon monitoring

Greater effort should be made to actively monitor carbon gains and losses via remote sensing. Technologies to do this are rapidly advancing as new satellite sensors are proved (e.g. Li et al. 2018). Such a shift may allow carbon credits to be gained through response measures that increase sequestration rates above those of the unmanaged forest[43].

Any need to measure carbon and report forest carbon stocks, stock changes and the impact of management on forest carbon stocks at the estate level risks increases the burden on forest managers. It will be challenging to get accurate data and evaluate scenarios under current management approaches. There is also a risk that increasing regular reporting of forest carbon stocks may create a focus on short-term landscape-stored carbon as a response to carbon pricing and climate change, which may not promote the best long-term forest management. A model is needed that integrates with company inventories to allow carbon to be optimised/managed using current approaches to managing forests for timber volume. Any move to develop a parallel carbon inventory and management approach is not likely to be used (being too costly to run). Such a federally approved model/approach is not readily available in Australia, although the commercially available FLINTPro, based on the Australian model FullCAM and an inventory-based approach from Canada[29] can extrapolate point data to the landscape scale and has been tested and applied in New South Wales. Although it should be noted that the scientist who developed FLINTPro remarked that the available figures for soil carbon are often undependable (P.D. McIntosh, pers. comm.).

Develop policies and practices to better manage carbon

Policies and practices could be enhanced/developed to balance carbon as one value among many[29].

Reduce prescribed burning

Prescribed burning involves a trade-off between an outlay of carbon emissions from frequent treatment and potential emissions savings from less frequent wildfires. There are several ecosystems where it has been argued that increasing the rates of (low severity) prescribed burning will reduce CO_2 emissions (see Bowman et al. 2020 for refs). However, there is some evidence to suggest the trade-off may not be beneficial in southern Australian eucalypt forests (Bradstock et al. 2012, cited by Bowman et al. 2020). In these areas the objective of prescribed burning is to maintain the forests in a relatively low-fuel state, so that subsequent wildfires are inhibited. However the carbon emissions from this prescribed burning strategy may emit more CO_2 in the long-term than infrequent wildfire.

5.2.5. Increase use of forest products

Use forestry residue to produce bio-energy

Forest residues can be processed and used as a biofuel, which could provide an alternative to the widespread use of fossil fuels in Tasmania[33]. While the processing of the biofuels would require energy and burning biofuels produces similar emissions to fossil fuels, use of biofuels would substitute for fossil fuels and therefore reduce carbon emissions when considered at a global scale[29]. Furthermore, the economic returns from selling biofuel should provide more resources to forest management[29].

‘Increased biomass use for energy could lead to lower carbon stock and lower sequestration rate in the forest compared to a scenario with less biomass use. However, an increase in demand for bioenergy and other forest products can also incentivise reforestation and improved forest management to increase growth, potentially increasing forest carbon stock compared to the without-bioenergy situation.’ (IEA Bioenergy 2020).

When considering the carbon benefits of using biofuel, it is important to consider all components of the supply chain. ‘Fuel use for collection, chipping/pelletising and truck transport typically corresponds to less than 10–15% of the energy content in the supplied biomass. Moreover, studies have found that long-distance transport does not negate the climate benefits of biomass as a renewable energy source. For example, GHG emissions associated with transporting pellets between North America and Europe represent less than 5% of the life cycle GHG emissions of hard coal’ (IEA Bioenergy 2020).

‘Sustainability governance is required to avoid or mitigate adverse outcomes for the climate and to manage trade-offs with other societal goals. A key requirement is that forests are regenerated and that carbon uptake capacity in the forest is maintained (such as specified in the Recast of the EU Renewable Energy Directive)’ (IEA Bioenergy 2020). It should also be monitored whether harvest levels increase as a result of biofuel production, which may have negative implications for other forest values[46]. If harvesting was focused on biofuel production it may lead to short rotation intervals with implications for carbon sequestration[51].

Produce carbon friendly products and minimise forest residue

Regrowing forests, minimising forest residue and producing carbon friendly products from harvested timber will increase the proportion of carbon entering long term storage[25].

Solid wood products in construction can be used as substitutes for other carbon intensive materials, such as steel and aluminium, that rely more heavily on fossil fuels for their production. The industrial process that makes concrete results in direct carbon emissions as calcium carbonate is thermally decomposed producing lime and carbon dioxide. The use of wood, particularly engineered or mass timber products such as glulam and cross laminated timber, as substitutes for these other carbon intensive building materials is becoming more common however there is enormous potential for growth in these markets[53]. Increasing domestic processing will also reduce the carbon miles of any products created.

Increase promotion of carbon-friendly products and user-knowledge

The forest industry could be seen as a solution to carbon challenges by facilitating carbon capture in growing forests, storage in wood products, or as an offset for emissions. The industry could focus on either carbon capture or storage which would result in different management practices. Greater public understanding of the role of forestry in carbon management would help improve the social license of the industry and potentially guide decisions on future land use management[29].

Carbon could be a driver of forest management; it could support establishing new trees in farmland and continuous improvement of forest management – while delivering society with a range of benefits. Carbon credits are currently too low and not front-end loaded enough to cause this to happen at scale now. Current methods focus on landscape carbon storage and not enough on the benefits of wood[29].

The carbon market may a good means to drive forest management for carbon outcomes, as it can be applied across the economy without focussing on one aspect such as storing carbon in landscapes using an agreed method. Agreed methods are generally restricted to coupe scale operations and so far are not applied to the landscape scale where forest management occurs[29] (but see 5.2.4 ‘Improve carbon monitoring’ above). The implications for selling carbon sequestration interstate or overseas would need to be fully understood.

5.3. Research needs

5.3.1. Monitoring

- Need improved carbon accounting of forestry emissions, particularly native forests and how carbon emissions and sequestration vary with different management interventions and silvicultural regimes.
- Need greater understanding of the conditions under which Tasmanian forests switch from carbon sinks to carbon sources[3].

- WARRA is currently the only carbon monitoring station in Tasmania and even WARRA is insecurely funded with the tower presently damaged and not recording data[45]. Other locations for monitoring carbon sequestration should be established, and there are relatively affordable options now available (e.g. stem dendrometer bands).
- Need better information on the result of climate change on soil carbon stocks.
- Do research to calibrate timber volume with carbon for different forest types.

5.3.2. Effectiveness of adaptation options

- Explore the outcomes of avoided harvest (rely on stored carbon, although some forest types may continue to sequester carbon[51]) compared with increasing sequestration rates (through active management), accounting for carbon emissions from the operation including regeneration burns [43].
- Risks of carbon loss due to physiological responses to higher temperatures for key species[29].

6. Forest vigour and condition

The use of the term ‘forest vigour and condition’ in the context of this report relates to the growth and survival of the trees and forests, and the integrity of the forest communities.

6.1. Potential impacts

6.1.1. Forest productivity

Tree growth may increase in some areas, but decrease in others

Increased CO_2 concentrations may increase tree growth in some areas (Jiang et al. 2020; Walker et al. 2019), although the impact is likely to be greater for younger forest than mature forest[43]. However, the potential benefits from increased CO_2 are unlikely to exceed the damage caused by increased temperature (Gattmann et al. 2021; Brodribb et al. 2020).

Long-term data shows that the growth rate and height potential of native eucalypt forest in Australia is sensitive to temperature, with highest growth on sites with mean annual temperatures around 11°C and a maximum average temperature of 25–27°C. However the response will be species- and location-specific[4]. Whether an area will be negatively or positively affected is likely to depend on whether the forest is water limited or not water-limited. Tree species that occur on mainland Australia as well as Tasmania may be at lower risk or may even see improvements in health or range extensions, though this will be dependent on genetic variability and phenotypic plasticity[4].

While there is likely to be variability, overall a decline in forest productivity is expected (Trouve et al. 2021). The relationship between temperature and net ecosystem exchange (photosynthesis/ respiration) at Warra suggests there has been an estimated 6–7% decline in productivity since the 1990s (Wardlaw 2016) and trees in the area stop photosynthesising when they reach a particular temperature (which varies between species and areas). A prediction has been made that productivity will decline by >20% by 2070 if the increase in temperatures reaches 3°C above 1900 levels (Bowman et al. 2014b) [43]. In addition there have been observations of tree mortality and dieback events state-wide which suggests that forest eucalypts in Tasmania have experienced increased stress and less favourable growth conditions in recent decades. Climate change models suggest that this trend will continue to worsen, potentially rapidly[28].

In plantations, nutrient availability may determine whether the growth rate experienced by eucalypts increases or decreases with elevated CO_2 levels and growth rates of radiata pine are likely to decrease (Keenan et al. 2020).

Drought stress can reduce forest productivity and increase tree mortality

Drought stress can trap gas emboli in the hydraulic system of plants, reducing the ability of plants to supply water to leaves for photosynthetic gas exchange, potentially leading to tree desiccation and even death (Choat et al. 2012). This means many forests may face reductions in productivity and survival under warmer, drier conditions (Choat et al, 2012). Young forests have not had time to establish deep root systems to help them access deeper water sources, so they are likely to be more vulnerable to drought.

In forests experiencing high temperatures, some trees close their stomata to reduce water loss and thereby reduce photosynthesis (van Gorsel et al. 2016, Gordon et al. 2018). This is another way that drought can result in reduced rates of tree growth or death. Trees in water-limited (i.e. dry) forests are expected to be more vulnerable.

Stressed plants are also more susceptible to pests and diseases, see Section 11 for further discussion.

Changes in productivity will depend on the optimum temperature for photosynthesis for that forest type.

Temperatures that are above the optimum temperature for gross primary productivity for the site will result in photosynthesis declining and respiration increasing. This combination causes a rapid drop in the net productivity (gross primary productivity - respiration) and can result in the forest becoming a source for CO_2 (Duffy et al. 2021). The optimum temperature for photosynthesis of a site is directly related to the historical climate of that site (Bennett et al. in review) [43]. Tasmania's wet eucalypt forests have a low temperature optimum for productivity, with a very sharp drop-off in productivity as temperatures move away from the optimum (Bennett et al. in review). This means the productivity and health of Tasmania's wet eucalypt forests are very sensitive to increases in temperature and so rapid declines in productivity may occur under a warming climate[43].

The impact of temperature on plantations is likely to be dependent on the species and genetic stock of the trees.

Pinus plantations are unlikely to experience the temperature sensitivity of photosynthesis (Way and Oren 2010) [43]. The amount of land suited to growing *E. globulus* may increase under climate change, so some plantings of *E. nitens* could be converted to *E. globulus*[47]. In areas where the primary aim is timber production, other mainland tree species may become more suitable to plant over time[47].

Some impacts will be episodic rather than gradual, such as heatwaves

Heatwaves are particularly impactful – the November 2017 record heatwave in Tasmania likely saw the forest at Warra switch from a strong carbon sink (uptake of 21 kg C/ha /day) to strong carbon source (loss of 19 kg C/ha/day) during the heatwave and the annual productivity of the forest more than halved compared with 'normal' years based on monitoring of carbon, water and energy fluxes at Warra (Wardlaw 2018).

Heatwaves may also trigger mass mortality events.

The geographic area in which plant species are best suited to growth is likely to change over time

We are likely to see changes in the geographic areas in which forest tree species are best suited to grow. This could be a result of the combined effects of temperature and changes in CO_2. In native forest stands, the climate envelope of understorey species will also change, resulting in changes to above and belowground ecosystem forest processes – which will affect forest trees of commercial interest.

Wood quality can be impacted by drought

E. globulus is prone to excessive kino-pocket development in response to high temperature events (e.g. heatwave of January 2014 in northern Tasmania). Such damage does not kill the trees, but the wood of affected trees becomes unsuitable for solid-wood products[43].

6.1.2. Tree survival

Tree mortality is expected to increase, but will be species and location specific

Globally there is a documented increase in tree mortality due to drought, heat waves and insect/ disease outbreaks (Allen et al. 2010). There has already been dieback documented in Tasmania (*Eucalyptus gunnii*)[4]. Gradual changes are expected to occur at the leading edge of a species distribution (i.e. species will migrate slowly) whereas abrupt changes, due to mortality, will likely occur at the trailing edge (i.e. disturbance will exacerbate change)[4]. Species can persist within a broad range for a considerable period, but then hit a tipping point where there is high mortality or reduced growth rate. Climate change (maximum temperature and rainfall) is heading towards the maximum tolerance levels of what local eucalypts can deal with[8,38].

Drought events are expected to cause increased mortality in tall eucalypt forests

Past episodes of 'regrowth dieback' events in tall eucalypt forests in Tasmania have been linked to drought. However, the role of coinciding high temperatures was not considered. Dieback during the summer of 1982 occurred in response to record high temperatures in many parts of southern/central Tasmania coinciding with drought conditions (T. Wardlaw pers. Obs.). Such coincidence is likely to become more frequent as temperatures increase.

Evidence from the extensive drought-related forest mortality event in 2019 on mainland Australia suggests that forest mortality due to acute water stress can become catastrophic over a short period, leading to impacts over thousands or millions of hectares. The damage caused by such dehydration is different to and may have a longer recovery time than damage caused by fire[45]. Tasmania's topography is likely to restrict the extent of such events, but the drought vulnerability of many Tasmanian eucalypt and rainforest species suggests that impacts are likely to be substantial in the next decades[45]. For example, recent research has found that the tall *E. obliqua* forest at Warra is particularly vulnerable to drought damage because it has a very low hydraulic safety margin, which means that it can rapidly reach a point where the hydraulic function of the tree fails (Peters et al. 2021). Some global research has shown that hydraulic safety margins are narrow (<1 megapascal) in many forest species, independent of mean annual precipitation (Choat et al. 2012).

High temperatures, particularly when associated with low rainfall, are expected to increase mortality in eucalypt forests

Increasing temperature, regardless of whether it is accompanied by intensified drought (which is also likely), will see greater evaporative demand on trees. This in itself has the potential to cause crown damage on extreme days, but in combination with more rapid soil drying, will cause an increase in water-stress related tree mortality, which will begin to have a substantial impact on Tasmanian forests in the next 10–20 years. This appears to have already occurred in east coast *E. viminalis* forests and highland *E. gunnii* forests. Medium hot-dry events are likely to cause moderate damage, reducing carbon-assimilation for sustained periods. Extreme hot-dry events are likely to cause catastrophic damage to trees and associated forest systems[45].

The coincidence of unusually low rainfall and high temperature have been linked with past dieback and mortality. Using these two weather attributes Mitchell et al. (2014) were able to determine thresholds for mortality. Mortality in north-east Tasmania (Swansea) was tracked in real time with xylem cavitation appearing (prelude to mortality) as weather thresholds for damage were exceeded during the November 2017 heatwave (Skelton et al. 2017) [43].

Weather that triggers many (but not all) dieback/mortality syndromes (Wardlaw 1990) also favours fire, although fire and dieback have only rarely overlapped spatially (the Great Pine wildfire of 2019 was one exception)[50]. Gully Dieback in north-eastern Tasmania was triggered by an extreme drought in 1967, but fires during the same drought were restricted to southern Tasmania. In the absence of disturbance there may be a progressive loss of eucalypts from some forest communities.

Drought will be the main climate-driven cause of mortality in eucalypt plantations.

Localised mortality of plantations is common in drought-prone situations (e.g. shallow soils or stony terrain), but widespread mortality is rarer and is typically associated with extreme drought such as occurred in 2006 and 2007. Analysis of publicly owned plantations in Tasmania found drought-induced mortality was concentrated in the driest sections of the plantation estate, which made relatively small contributions to the overall productive potential of the estate (Wardlaw 2010). However, such observations are estate-specific and depend on the location of the plantations.

6.1.3. Forest reproduction

Repeat fires may impact seed production of some species

Increasing air temperatures, prolonged droughts and frequency of dry lightning storms is leading to wildfires in short succession. Repeat fires over short time intervals can potentially lead to natural regeneration failure of important obligate-seeding tree species such as *E. regnans* (Keenan et al. 2020). These short fire intervals may result in more extensive immature forests, which do not produce seeds[35]. Although seed production may occur at a younger age if trees are growing well, for example if conditions are not too dry[12].

Changes in timing and efficiency of reproduction

Climate change may impact the timing of flowering for some species, which may affect the effectiveness of plant pollination (e.g. Parmesan & Yohe, 2003). For example it is possible that plants may synchronise the timing of their flowering by photoperiod while pollinators' reproductive timing may be dependent on cumulative temperature[5], but one respondent argued that Tasmanian pollinators are almost entirely generalists so this was unlikely to be a problem[51].

Reduced frosts may impact the reproductive capacity of species that require cold temperature-induced dormancy for germination (Keenan et al. 2020). Some eucalypts require a period of low temperature (vernalisation) to trigger the initiation of flower buds. At higher annual temperatures this vernalisation requirement is not met, and flowering is not triggered. The initiation of flower blooming in some eucalypts is controlled by heat sum, so under warmer conditions, trees will flower earlier in the season. Warmer conditions can also lead to the production of larger and more vigorous germinating seed in eucalypts (Williams 2000).

The reproductive capacity of some organisms may decline under climate change, and this may occur unnoticed, for example prior to the onset of severe vegetative symptoms. In the case of *E. gunnii divaricata*, when the stands started dying and people wanted to collect seed it was already too late[8].

Lower seedling establishment

Plants in temperate forests in south-eastern Australia are most sensitive to environmental change during the germination process and subsequent establishment (Bell and Williams, 1997, from Mok et al. 2012). Future warmer drier conditions are expected to result in reduced seedling establishment of some species (Rawal et al. 2015, Mok et al. 2012)[22]. The drier forest ecosystems may experience more severe declines in regeneration potential than wetter forests, and species with seed dormancy mechanisms (e.g. *E. delegatensis* and *E. pauciflora*) may be particularly vulnerable (Mok et al. 2012). However, phenotypic plasticity within regeneration may help sensitive species to adapt through phenotypic acclimation and eventually through genetic selection (Mok et al. 2012).

Some species may also need to shift their seedling establishment niche in response to climate change. An example of this is *E. gunnii* subsp. *divaricata* where a shift was observed in the micro-sites where regeneration occurred to areas with greater water holding capacity (Sanger et al. 2011). The authors argued that this was most likely a response to changes in the timing of the rainfall (as opposed to annual rainfall) (Sanger et al. 2011).

Young forests may be particularly susceptible

Regenerating forest may also be more sensitive to wildfire, and in some instances have poor regeneration following wildfire[34].

The rate of hybridisation may change among species

Hybridisation between species occurs naturally and it is possibly an important part of the process of species range expansion and contraction in response to climate change. For example, as areas become drier they may favour *E. obliqua* over *E. regnans* which may be mediated through hybridisation (Ashton 1981)[8].

A previous assessment of the risk of hybidisation between *E. nitens* used for plantation forestry and native Tasmanian species found that flowering asynchrony created a potential barrier to pollen-mediated gene flow (Barbour et al. 2006). Flower blooming can be triggered by environmental cues such as the 'seasonal heat sum' (Barbour et al. 2006), which varies among species. This could mean that the present barrier to hybridisation may change for some species. It should also be noted that hybridisation may be part of the evolutionary process that allows forests to adapt to changing environmental conditions[8].

6.2. Potential adaptation strategies

6.2.1. Forest regeneration

Sow more seed after disturbance events

Natural selection is likely to facilitate growth of the most well-adapted and strongest individuals. Current forestry practices sow adequate seed for regeneration, but some respondents argue this is insufficient to ensure strong natural selection[45]. With greater competition from more seed, the individuals best suited to current conditions should flourish and get taller and put on volume more quickly[45]. However, there is also the risk that higher stem densities and taller trees may result in fewer resources per tree, which may make the trees more susceptible to other factors like drought[8]. Therefore the effectiveness of this strategy may vary with forest type[46].

Collecting seed is expensive, so this process comes at a cost, particularly if you are trying to include a wide gene pool in the seed. Low altitude mega seed zones along the north and east coast as well as inland north-east Tasmania will likely be important sources of seed for future reforestation projects (Harrison et al. 2020).

Collect and sow seed from local areas potentially adapted to warmer temperatures

Tasmania has experienced a number of warmer summers over the last few decades. While not yet scientifically determined in Tasmania, it is plausible that some degree of localised adaptation has occurred when forests have been subject to and regenerate under these warmer drier conditions. Sowing local seed that is potentially 'climatically adapted' could promote superior regeneration of forests following harvest, as local seed may be less susceptible to local pest species or pathogens than seed from non-local areas[43].

Vary the genetic stock of the seed sown

Many plant species are found in a wide range of geographic areas. Therefore, some genotypes are likely to be more drought, heat, pest or fire tolerant than others. Currently the *Forest Practices Code* states that native forest should be regenerated 'using seed from local or similar provenances in a manner that contributes to the maintenance of genetic diversity, taking into account the potential of ecosystems and species to adapt to climate change'.

Using a mix of seed from local and more climatically suitable areas has the potential to help ensure the regenerating stand is vigorous under both current and changing climate conditions. To vary the source of the seed effectively requires a good understanding of optimum seed locations, and the percent mix of introduced and local seed should be considered. The introduced seed could be sourced from Tasmania, or from mainland Australia. This practice has been occurring in places like Canada for years[8,38].

It is possible that biotic interactions (e.g. local pathogens) may mean seed from out of area may not work well, but sowing with excessive seed will allow the process of natural selection to occur[8,38]. This practice would mean that the genetic identity of a local provenance is lost, but it will increase on-site genetic variability and there should be no reduction in genetic variability overall. Some work has already been done to identify potential areas of suitable seed for different geographic areas, and for key eucalypt species (Harrison et al. 2020).

Collect seed from optimum seed provenances

Regardless of whether the decision is made to vary the genetic mix of seed now or not, it is important that the option of using climatically adapted seed is available. Consequently, seed should be collected from a range of areas, particularly areas that are more climatically analogous to future conditions.

Climate profiles exist for many eucalypt species[45], so it would be a relatively simple exercise to develop a spatial layer to predict the 'genetically optimal' seed locations in Tasmania for modelled future climates of a planting site. These areas could either be reserved as future seed source areas, or they could be monitored and regularly harvested for seed.

Plant more climate suitable species

In some situations it may be appropriate to plant different tree species that are more climatically suitable than existing (or previous if there has been mass mortality) species. Alternative species could be used instead of, or in addition to existing species to regenerate forests. Productivity is improved if you have diverse species, because species respond differently to different conditions. Sowing alternative species may change the forest community but if selected appropriately they should perform the same ecological function and create an ecosystem that has more resilience[4], [12]. Planting alternative 'climate suitable' species is already occurring in parts of North America[4].

The sowing/planting of different species is not a process that should be undertaken lightly. The viability of different species would need thorough testing (e.g. for the presence of suitable mycorrhizal fungi[51] and for long-term performance[47]) and a thorough understanding of the ecological consequences of planting different species would be needed. For example, in a plantation context, pines are more tolerant of low rainfall and drought conditions than eucalypts and they can be more productive on these sites. However, this comes with implications for other factors such as biodiversity and risk of weeds[8].

Regenerate areas that have suffered large mortality events

In areas that have suffered major dieback, it may be appropriate to harvest and regenerate the forests to restore ecosystem function[43], although the surviving trees may also be an important source of 'climatically adapted' seed[8]. Alternatively, the stands could be subject to a planned burn shortly after dieback to promote regeneration[51]. Currently there is no requirement under the forest practices system to remediate stands suffering long-term or permanent damage as the result of stress events. In addition, there are no standards that define thresholds of reduced forest values due to dieback and mortality[43].

Minimise soil compaction during forest management

Compressed soils have lower levels of forest regeneration. Reducing the use of skidders, or exploring ways of reducing the impact of skidders (e.g. pulling a plough) may improve plant regeneration[12].

Review silvicultural practices

The silvicultural system used to harvest and regenerate a forest stand is typically selected according to the ecology of the tree species in the area, the historic disturbance regime and social pressures. Nitsche and Innes (2008) argue that the resilience of the ecosystem to climate change should also be considered, as different silvicultural systems have different impacts on the microclimate of the stand and therefore the success of the regeneration. In regenerating forests the microclimate can be affected by distance to retained forest, time of day and forest age (Baker et al. 2014). Some respondents argued that the use of clearfell silviculture in native forest stands (and potentially planted forests) may become increasingly inappropriate under climate change, as plant responses to such intensive silviculture may struggle to regenerate under drought conditions[23,50].

Many silvicultural practices seek to emulate natural disturbances but understanding of the difference between these types of disturbance continues to grow. For example, Trouve et al. (2021) examined *E. regnans* regeneration after catastrophic wildfire and found that regeneration density after wildfire was nearly two times greater but patchier than regeneration from aerial sowing after harvest (Trouve et al. 2021). New silvicultural systems that provide alternatives to clearfelling, such as aggregated retention, have been increasingly adopted (Fedrowitz et al. 2014). One drawback of variable retention silviculture can be the negative impact of the increased influence of forest edges on regrowth vigour (Baker et al. 2019). However increasingly hot and dry conditions may impact the relative vigour of regeneration in relation to proximity to a forest edge.

6.2.2. Improve forest resilience

Forest thinning

Thinning forests increases the resources available for individual trees, allowing them to reach target size on shorter rotations (note: high competition when seedlings establish can promote rapid growth in the early stages, but this effect lasts only a few years after which adequate resources will have greater impact on tree growth). Promoting rapid growth in regenerating stands can be particularly important if the aim is to increase the resistance to drought or to fire-induced mortality. However, thinning may only be a useful tool in areas where water is really limiting and may be impractical for large-scale application[4, 12] (Keenan et al. 2021)[43]. Where applied thinning should be done with care as it can result in increased soil compression, and in some areas may result in drier forests with combustible material on the forest floor making them more fire susceptible (Taylor et al. 2020)[34].

Maintain mature trees and forest

Older trees are more resilient to drought and fire, so maintaining mature trees and forest patches in the landscape should help improve forest resilience to bushfires and climate change[18]. The usually lower flammability of old forest patches would help reduce the rate of spread of landscape-scale fires and increase the chance of fire patchiness, leading to unburnt forest islands[18].

Sow understorey species

Plant diversity promotes resilience, because different species support a range of environmental values and different species also respond differently to changing conditions. Regeneration of the forest understory following harvesting is not specifically considered when planning forest operations. How well the original understorey species persist following regeneration activities is highly variable. Some species regenerate well, while the seeds of many understorey species do not persist in the soil. Understorey regeneration tends to be particularly low if the time interval between harvest and the regeneration burn is long (several years). However, the process of obtaining adequate amounts of understorey seed is extremely expensive. So alternative methods such as smaller coupes or alternatives to clearfelling may be more practical[12]. Sowing understorey species may also help restore the microclimate of the area more quickly, promoting forest health[51].

Reduce harvest rotation intervals

There is no direct evidence that temperature sensitivity varies with forest age, but extensive surveys in the 1970–80s found evidence of dieback in older but not young forests[43]. This may indicate that younger forests are less sensitive to warmer temperatures, in which case harvesting production stands more frequently may maintain higher productivity overall[43]. However, the postulated reduced sensitivity to warming temperatures in younger forests would need to be verified before adopting the strategy[43] as the shallower root depth and higher density of young forests may make them more sensitive to temperature-associated drought impacts[45]. The implications of shorter rotations for wildfire risk, biodiversity, carbon, seed production and wood quality would also need to be considered[34].

Reduce clearfell-burn-sow (CBS) silviculture

The current silvicultural practice of clearfell-burn-sow for production forest regeneration produces more homogeneous stands than is produced by natural disturbances such as wildfire[22]. Retained trees and patches are important sources of seed (and potentially soil biota) for the regenerating forest. Applying alternatives such as aggregated retention, retaining a network of unlogged patches and fire refugia should help produce healthier forests and increased biodiversity (flora and fauna) [12]. However, in aggregated retention, there is a larger proportion of the coupe subjected to edge effects from the adjacent forest. These edge effects can diminish the vigour of tree growth (Baker et al. 2019)

Papers have been written on how to do climate-smart forest management (e.g. Nitschke and Innes 2008). Some suggestions under this banner include using uneven aged silviculture that maintains cooler, moister conditions that can promote recruitment of drought and frost sensitive species[4].

Maintain heterogeneous vegetation – smaller and dispersed coupes

Diverse vegetation mosaics tend to be more resilient than uniform vegetation cover, so forest cover of different types and age is likely to be better for forest health. This can be achieved by having smaller coupes (which would also make it easier for understorey species to regenerate) and dispersing coupes spatially and temporally[12]. Being closer to a forest edge mitigates some of the impacts of clearing on microclimate, so having smaller coupes, or different shaped coupes may help trees regenerate under a changing climate[51]. However, edge effects can reduce the vigour of regenerating trees (Baker et al 2019) and the close proximity of food to established forest edges or other cover can lead to increased feeding by macropod herbivores in young forests (While and McArthur 2006).

Active plantation management: Fertilise, weed suppression, browsing suppression

There are a number of changes to plantation management that may improve the health of planted forests moving forwards (Keenan et al. 2020). Fertilising stands can promote crown recovery after insect defoliation. This practice is more appropriate for plantations than native forest. However while fertilising can increase productivity, it may also increase mortality in water limited environments[35].

Other techniques used in plantation forest settings (this list is not exhaustive) include

- hardening radiata pine nursery seedlings by increasing root:shoot ratios and planting containerised rather than open-rooted seedlings
- controlling weeds for up to three years following establishment
- fallowing sites to reduce water stress and to increase stored soil water
- planting on mounds to reduce impacts of waterlogging on sites receiving heavy inundations
- use slow-release water crystals/gels or biochar
- reducing populations of browsing animals.

6.2.3. Protect important values

Protect rare or high value species

Some rare or high value species may need greater active management or protection under a changing climate. Areas most resilient to climate change could be identified to help protect these values[47] and would be important locations to monitor and potentially actively manage if required[46]. Vulnerable ecosystems, species, habitats etc could be modelled as per Nitschke and Innes (2008)[34] or using tools such as those provided by AdaptNRM.

Increase streamside reserves

Changes in rainfall patterns and increasing magnitude of extremes flow events may be ameliorated to an extent by increasing streamside reserve provisions [28]. Widening streamside reserves, particularly in headwater streams, will help maintain the microclimate of these important areas[51].

6.2.4. Improve capacity to adapt to change

Improve forest health monitoring

While capacity to monitor and assess forest condition has improved in some parts of Australia, there are gaps in monitoring potential risks. Improved monitoring can facilitate the implementation of alternative management options to address key risks. This will require national investment and coordination across states and research organisations to detect emergence of key risks such as declining tree health, insect pests or disease outbreaks, reduced water availability and changing fire regimes. Remote sensing tools, data science and new technologies such as drones, remote cameras, acoustic recorders and satellite imagery can significantly reduce the costs of forest monitoring. Combining ground plot information and real-time remote sensing will be needed to detect real-time tree stress and mortality events.

Plan forestry at multiple spatial and temporal scales across tenures

Many of the issues likely to be exacerbated by climate change, such as wildfire and drought, occur at larger spatial scales than the forestry coupe. As such, planning needs to incorporate large temporal and spatial scales to be able to address these issues. This may involve zoning areas of forest according to their resilience or vulnerability to climate change and related stressors (Nitschke and Innes 2008).

Adjust sustainable yield calculations and harvest levels

The amount of harvesting occurring in the landscape has direct implications for how some other actions may be achieved (e.g. heterogeneous landscape). Estimated sustainable yields (and legislated harvest levels) need to account for the fact that forest productivity is likely to decrease in many areas, and unplanned disturbances such as wildfire will remove large areas from the available resource[43].

Develop an adaptive and collaborative management approach

There are significant unknowns about the exact nature of, and rate of onset of impacts from climate change. Developing and maintaining the ability to rapidly make or change decisions or processes in response to emerging threats, impacts or changes would enable rapid adaptation decisions to be made where and when necessary[28].

When climate patterns, including extreme events, remain within the bounds of those experienced historically, past practice can be used as a basis for future management. Once climatic conditions move outside this range, new practices are likely to be required. Past strategies used by the forest industry involve locally based, autonomous decisions. Preparing for, and adapting to, more extreme climate will require policy and infrastructure support and greater planning at regional and national levels[35].

Adaptation will require science-based strategic planning which will require knowledge of:

1. Species vulnerability
2. The use of process-based modelling-to determine which species to plant
3. Forest monitoring to understand when trees are becoming impacted by climate considerations

Having flexibility to adjust wood-production plans will allow early harvest and regeneration of areas that have suffered significant, long-term or permanent damage from stress events in wood-production areas.

6.3. Research needs

Forest monitoring

Monitoring forest condition allows the industry to effectively respond to climate change impacts in a timely way and facilitates alternative management options (Keenan et al. 2020). While capacity to monitor and assess forest condition has improved in some parts of Australia, there are gaps in monitoring of potential climate induced risks. As stated above, improved monitoring can help facilitate the implementation of alternative management options to address key risks.

Some key monitoring projects are outlined below:

- widespread monitoring of tree health, water availability and fire regimes
- mapping the spread of weeds, diseases such as myrtle rust (*Puccinia psidii*) and pest outbreaks
- monitor and better understand forest water use (e.g. more monitoring such as Warra flux tower) [45]
- species populations and distributions.

Climate vulnerability/response

We know very little about the ecology of most of Tasmania’s biota, including flora, fauna and other groups such as fungi. Understanding their vulnerability to climate change through quantifying their ecology and links to climate and disturbance are much needed avenues of research[4].

Some key potential projects are outlined below.

- Our current understanding of the effect temperature-sensitivity has in Tasmanian forests is based on measurements made at a single site (Warra), although corroborated by findings from analysis of forest inventory plots. Further research is required to understand temperature-sensitivity of the other forest types and in other areas of Tasmania[43].
- Physiological tolerances (e.g. to fire and drought) of Tasmanian species (Brodribb's research)[48]. This may include specific information connecting weather and plant stress (monitoring required to produce transfer functions for modelling) and consider forest age classes. This could be used to model the effect of temperature and rainfall on tree productivity, accounting for topographic variation, to predict future impacts[45].
- Reciprocal experimental trials to understand which key plant species and genetic stock within species does better across large scale geographic areas, and what may be appropriate mixes of local and introduced genetic stock. Some of this work is already being done by UTAS (e.g. Potts and Harrison's research).
- Forest harvesting is an episodic, stand-scale event and harvesting operations are likely to be one of the times when production forests exhibit rapid climate related change, either in terms of potential risk or adaptation. Modelling will help understand the role of forest harvesting in precipitating climate-change induced changes to the forest system, and thereby identify mitigating measures[28].

Effectiveness of adaptation options

A lot of adaptive measures have been suggested, but our understanding of how effective these measures are is often poor.

- Determine if there is a relationship between forest age and temperature sensitivity[43].
- Determine the rate of local provenance adaptation to new climatic conditions (i.e. determine if plants that established under historic warm dry condition are more climatically adapted)[43].
- Validation of the predictions from non-local provenance use (e.g. translocations) and strategies such as such as climate adjusted provenancing[8].
- Determine the stand development stage(s) where selection for a higher temperature optimum for productivity is likely to be strongest[43].
- Research on the role of ecological thinning silviculture in reducing impacts of heat stress in regenerating stands[48].
- The impact of thinning on understorey and other ecosystem attributes[41].

Modelling long-term implications

The impacts of climate change, and potential implications from proposed adaptive measures will not be certain for long time periods. Modelling is important to try and improve our understanding of how the forested system is likely to respond to these changes.

- A major source of uncertainty is the current landscape-scale variability in forest structure and composition, the development trajectories of the individual stands, and how the emergent properties of the landscapes can (or cannot) buffer the impacts of a warming climate on the forests. In Victoria, for example, the 2009 bushfires in the Central Highlands created tens of thousands of hectares of extremely dense regenerating stands. These stands may be more prone to drought-induced mortality, grow more slowly, and take longer to reach fire-safe sizes than stands that regenerate at lower densities. This problem stretches across tenures and is widely unappreciated[22].
- Ensure sustainable yield calculations account for changes in productivity and disturbance such as wildfire or dieback.
- Formal analysis is needed to model changes in forest values due to losses from dieback and mortality, and set action thresholds.
- Our current understanding of the impact of climate on forest health mainly comes from diagnosis of individual dieback and mortality events where an association is made with anomalous climate events which are predicted to become more prevalent with climate change (Wardlaw 1990). Collation and analysis of historical records of past events can identify damage thresholds for climate anomalies (e.g. Mitchell et al. 2014), which can potentially be used to forecast changed risks due to climate change (Mitchell et al. 2016) [43].

7. Fire

7.1. Potential impacts

7.1.1. Fuel availability

Wet and mixed forest will dry, making them more flammable

A drying out of wet and mixed forest is already occurring[19]. The number of times per year in which Tasmanian forests have been dry enough to burn has been rapidly increasing since at least 1990, and it seems that this is especially true in young stands following stand-replacement (0–15 years post disturbance; Furlaud et al. 2021b).

The susceptibility of wet forests to fire is dictated by the density and structural diversity of the canopy cover in the understorey (Kovácks et al. 2017, Norris et al. 2012, Cawson et al. 2017). A chronosequence study in Tasmania found that fuel loads didn’t change with stand age, but older forests had moister understoreys and more vertically discontinuous fuels and therefore had lower fire risk than younger forests (Furlaud et al. 2021b).

The amount of fuel available to burn changes over time since disturbance

Some studies have found that the number of days a forest is available to burn appears to be low immediately after harvest, peaks in the decades after as the forests self-thin and the canopy opens. As the canopy opens it lets in more radiation, which dries out these fuels. But as the canopy closes there are fewer days in which the forest is at risk of burning[1].

7.1.2. Ignition

More lightning has been occurring but future projections are uncertain

All fires need oxygen, fuel to burn and heat or an ignition source. How quickly a fire spreads and how intensely a fire burns depends on the type of fuel, the topography and the weather (mostly wind and temperature). There has been a massive increase in dry lightning over the past 45 years, but it is uncertain if this will persist in the future[17]. If, as expected with climate change, the mean path of atmospheric high pressure cells continue to track further south, then the level of atmospheric instability may decrease which would reduce the potential for dry lightning. The southward path of the highs will also result in decreased rainfall, meaning that if dry lightning occurs, it is more likely to result in a sustaining fire due to the drier condition of the forests.

The increase in lightning ignitions makes the location of ignitions less predictable and often less accessible (ignitions by people typically occur along roads/tracks) and means we are likely to face multiple (10–100s) simultaneous ignitions. This makes control of bushfires in the early stages of development difficult[31].

7.1.3. Fire conditions

Changed weather more conducive to fire

Fire weather predictions done about ten years ago are being redone[39]. Current projections, which show an increase in springtime fire danger, are playing out earlier than expected. The uncertainty in the rainfall projections has big implications for fire weather, because if rain comes in summer it may reduce the expected elevated fire risk[21].

7.1.4. Incidence of wildfire

Increased frequency of fire

The increase in temperature, likely decrease in rainfall and soil moisture along with the anticipated increase in evapotranspiration resulting in much drier soils and fuels on average than was the case a few decades ago, is resulting in a very large increase in the level of fire danger and average fire size along with a decrease in interval between fires[17]. Data indicates that between 1990 and 2020, the number of times sapling-stage stands were dry enough to burn increased from 80 days per year to 130 days per year, and in spar stage (i.e. young pole) stand from 20 days per year to 40 days per year[19]. Research suggests that, under high emissions scenarios, Tasmania will likely face general increases in the number of days of elevated fire danger across the state (Fox-Hughes et al. 2014). As such it can be reasonably expected that recent trends in fire occurrence and severity will either continue at current levels or increase in the future, and as such it is expected that more areas of Tasmania’s production forest estate will be subjected to fire, which may also include larger patches of severe fire[41].

Increased intensity and severity of fire

The fire regime of Tasmania's wet eucalypt forests can be currently best described as mixed-severity, which means that both crown fires and surfaces fires are possible in these forests when they are dry enough to burn. However recent research has indicated that surface fires are currently more likely than crown fires in Tasmanian wet forests, but that crown fires will become more common under a warming climate with more regular extreme fire weather (Furlaud et al. 2021a). Crown fires are a result of a higher severity fire. Current research indicates that the combustion of less-flammable, fire sensitive rainforest and sclerophyllous understorey species is probably necessary for a crown fire to occur[19]. Current research is indicating that fire weather conditions can have a greater impact on fire extent and severity than fuel loads (Collins et al. 2022).

Production forestry landscapes may be more fire prone

There is a hypothesis that young forests have an elevated risk of high severity fire, and that timber harvesting influences the prevalence of this risk across the landscape (Taylor et al. 2014; Lindenmayer et al. 2020). This hypothesis has been challenged by Keenan et al. (2021) on the basis that in the 2019–20 mainland fires the proportion of forested conservation reserves burnt was similar to that for public forests where timber harvesting is permitted, and the proportion of forest burnt with different levels of fire severity was similar across tenures and over time since timber harvest. Understanding of the role of forestry in promoting wildfire is still evolving, but for the 2019–20 mainland fires it appears that any role played by forestry was minor and the primary driver was the significant influence of fire weather (Bowman et al. 2021).

Forestry may impact fire proneness in a couple of ways. Residue left on the ground after harvest may increase fire risk in the short term. Younger trees (and potentially fuels in younger forests) can be more prone to desiccation under high fire risk conditions than mature trees due to smaller volumes and shallower roots. Young trees are also less resistant to the impact of fire than old trees (Clarke et al. 2013)[41]. However, the exact role forestry plays in promoting fire-prone landscapes remains unclear. A study in Tasmania found stand understoreys growing after clearfall, burn and sow silviculture are much drier and more vulnerable to fire than mature stands (Furlaud et al. 2021b), despite similar research from Victoria having come to conflicting conclusions (Burton et al. 2019; Cawson et al. 2017, Cawson et al. 2018). Other researchers have found that when severe or high canopy scorch is included in the assessment of a high severity fire, there is little difference between the likelihood of high severity fire between young and old age cohorts (Taylor et al. 2014; Bowman et al. 2021)[41].

The relationship between stand age and fire proneness may differ with forest type. In some forests 'extrinsic' factors like fire weather largely govern fire severity patterns (Bowman et al. 2016, 2021). In highly productive wet forest ecosystems, fuel is rarely limiting across a range of age classes and therefore fuel moisture becomes critical in determining fire occurrence (Cawson et al. 2018, 2020) [41].

Historically unburnt areas will become susceptible to bushfire

Given the expected increase in frequency and intensity of bushfires, areas that have not previously burnt will become more susceptible to bushfire. Critical infrastructure (e.g. communications towers, electricity assets, water supply) exists within or near to Tasmania's forest assets[6].

7.1.5. Forest change in response to wildfire

Increased frequency and severity of fire can impact forest regeneration and therefore forest type

Many eucalypt forest types are relatively resilient to fire and have effective mechanisms for recovery (e.g. resprouting). But some forest stands, particularly of the ash forest type (e.g. *E. regnans*), are more vulnerable to severe fire, and where future severe fire occurs this will likely result in sections of fire killed overstorey[41].

A change in the frequency and severity of wildfires (as observed and predicted) will impact forest mortality, growth and recruitment (Bowman et al. 2021). It is likely that all forests will be impacted, although the impacts may be more substantial in forests dominated by fire intolerant species[4].

One of the greatest risks is that with fire regimes moving outside the 'tolerable fire intervals' that key species can persist under, vegetation communities may irrevocably shift to alternative communities or forest types. As an example, several severe fires over a couple of decades in mainland Australia have been found to compromise the ability of eucalypts to recover via resprouting or by regeneration from seed if regrowth trees are not old enough to produce viable seeds by the time of the next fire (papers by Fairman and Bowman). In obligate-seeder forests, which do not resprout post-fire, two crown fires in short succession will cause ecological switching, where *Eucalyptus* forests are replaced by non-*Eucalyptus* forests as the young *Eucalyptus* seedlings do not have enough time to produce seed (Fagg et al. 2013; Bowman et al. 2014). However, in resprouting forests, which are more common in Tasmania (Furlaud et al. 2021a; Turner et al. 2009), the effect of repeated fires is poorly understood. While large, mature resprouting trees are resistant to two successive crown fires, younger trees (including in the spar stage) are more vulnerable (Collins, 2020). It is hypothesised that three successive fires in resprouter forests could have the same ecological effect as two successive fires in obligate seeder forests, causing demographic collapse (Fairman et al. 2016).

There are vegetation communities and individual species (e.g. rainforest and mixed forest) which will be particularly sensitive to repeated high intensity fires to the point where they might be lost from parts of the landscape[34, 41,46]. NRE Tasmania have used expert elicitation to understand the tolerable fire intervals (time between fires) for major TasVeg communities (Leonard 2021). Generally hotter and drier conditions driven by climate change may also impede post-fire vegetation recovery with lower vegetation survival, recruitment and growth even where seed stocks exist (Bowman et al. 2021) [19, 46].

7.1.6. Industry response to wildfire

Potential increase in post-disturbance logging or 'salvage harvesting'

Tree death due to increasing prevalence and severity of wildfire will impact product availability for Tasmanian forest industry. The industry will, where practical, seek to recover merchantable timber (e.g. salvage harvesting or ecological/restoration harvesting). In some cases where younger plantations or native forest regrowth sites are fire-impacted, landowners or managers may wish to clear sites and re-establish trees. These practices have the potential to negatively impact biodiversity and soils because they add a second disturbance (harvesting and site preparation) on top of the initial wildfire disturbance. It is thought that the double disturbance is likely to have particularly severe negative consequences compared to one or other disturbance type on its own (Lindenmayer et al. 2008, and others) [46].

Increased fire management efforts

One result of increased wildfire risk is that land managers may need to increase their fire management activities, such as planned burning and bushfire response. This in turn may impact the industry's ability to undertake other important management activities.

Increased forest regeneration efforts

The expected impact of repeat, high intensity fires mean there may be increased need to manage unharvested forest areas and non-production ecological values as they recover from bushfire[31]. For example, sowing of seed in unharvested forest may be required is natural seed stocks were low at the time of burning.

7.1.7. Planned fire

Carbon emissions from fire – planned or wildfire

Prescribed burning is used in natural forests to reduce fuel loads and to manage the type of vegetation. Traditional Aboriginal burning is thought to have been used deliberately to maintain grassy understory in dry forests and some tall-open forests. Since European settlement and elimination of fire from these landscapes the understory in these forests has changed to heathy vegetation or a secondary understory of shrubs and trees, creating ladder fuels to the crowns of the overstory which contribute to fire intensity and spread in extreme weather conditions. Ecological burns are now being done in some areas to try and change the vegetation structure and reduce fuel loads.

Fire is used following harvesting operations to reduce residues from treetops and other material left on the forest floor after harvesting. Removal of these residues for biofuel may reduce the fire risk to negligible levels (with negative implications for saproxylic biodiversity[46]). In plantation settings there is little use of fire for management activities, other than reducing residues that impact site preparation for subsequent rotations. The use of fire in these settings may be detrimental to maintaining long-term site productivity for certain sites.

While there can be considerable value in conducting planned burns, there is a trade-off between emissions generated from unplanned fires (i.e. wildfires) and fuel management through fuel reduction burning or vegetation management.

Reduced window to do planned burns

The change in climate, and associated change in fuel and soil moisture will mean there is a shortened window for conducting planned burns, including regeneration and ecological burns[17, 31]. This means there is a greater chance of unexpected outcomes and an increased level of risk when doing planned burns[17].

7.2. Potential adaptation strategies

7.2.1. Reduce incidence or intensity of fire

Manage landscape availability of fuel

Although managing the availability of fuel in the landscape is a sound concept, that may be more effective than reactive firefighting strategies[46], it is not necessarily clear how landscape availability of fuels can be effectively managed in practice[4]. Some options available include planned burning and mechanical removal (see below). Fuel management practices should be and are developed with consideration of the different forest types (wet and dry forests, rainforest) [46]. Areas at high risk of intense wildfire should be prioritised for these actions[48]. There can also be considerable social and political challenges to appropriately funding and actioning these activities.

Do more fuel reduction and ecological burns

Fuel reduction burns have become a widely accepted measure for reducing fuel loads, and thereby fire risk. The federal government has done a review on the role of fuel reduction burns for mitigating wildfires that concluded that while an effective component of broader strategies, it is not a panacea (McCormick and May 2021). Fuel reduction burns are not expected to stop a bushfire, but to slow its spread and reduce its intensity (McCormick and May 2021). In this capacity fuel reduction burns are likely to be effective under moderate or high fire conditions, but less effective under catastrophic conditions (McCormick and May 2021). An examination by Hislop et al. (2020) found that of 307 areas that had recent fuel-reduction burns, 48% showed decreased fire severity in the 2019–20 wildfire in NSW and Victoria. More recent fuel-reduction burns seemed more effective, but the authors did differences may be operationally insignificant under extreme conditions when wildfires are driven largely by weather irrespective of fuel loads (Hislop et al. 2020).

The design of fuel reduction burns will impact how effective they are, in terms of location, timing, frequency, size etc (McCormick and May 2021). Fuel reduction burning programs also need to carefully consider the degree to which burning reduces fire risk versus the impacts of short-interval planned burning on soil processes, site nutrition and the leaf litter, vegetation and aquatic communities, and carbon emissions[46]. To help design an appropriate burn program it could be worth considering and incorporating cultural land management practices and expertise from the Tasmanian Aboriginal community[48]. The time window available for conducting fuel reduction burns is reducing under climate change, so if this practice remains a key strategy, then increased resources are likely to be required to allow multiple planned burns to be conducted when weather is suitable[17].

Mechanical removal of fuels

Understory vegetation can be managed through the frequency of prescribed burning, or through mechanical removal[46, 47]. For example, mechanical removal may be a solution when understory vegetation grows to a stage where prescribed burning is no longer feasible. Mechanical manipulation could also be used to create firebreaks. Current preliminary results from Hobart City Council suggest mechanical thinning and removal of the understorey of spar-stage wet forests maintains a moister microclimate than prescribed burning does, possibly because less of the canopy is removed in thinning than through planned burns, and because maintaining litter on the surface helps buffer soil moisture[19].

Mechanical removal of vegetation is typically costly and logistically challenging and may be most achievable if done in combination with forest thinning operations[47]. Alternative industries such as salvage harvesting for firewood or biofuels may make the approach more feasible (see Volkova and Weston 2019, cited by Bowman et al. 2020). However, the implications for biodiversity of these strategies should be carefully considered as they could have negative consequences for site nutrition and for saproxylic organisms’ dependent on woody debris as habitat[46].

Forest thinning

Vegetation removal is one way to reduce standing fuel loads. Forest thinning is primarily a silvicultural treatment to promote growth on the remaining trees so they grow to a larger diameter in a shorter period of time. Thinning may be done on a commercial or non-commercial basis. Non-commercial thinning involves felling smaller trees or killing trees and leaving them standing to ‘release’ the remaining live stems. The dead material left behind in the forest following the conduct of these operations then becomes available fuel in wildfire situations and may need to be managed as a hazard.

Thinning currently occurs in some even-aged stands originating from previous wildfire or timber harvesting. In these areas, thinning provides wood products (albeit smaller diameter) and redirects growth to the remaining trees, increasing their size more quickly (La Sala et al. 2004). Larger trees are less vulnerable to drought and burning than younger trees[22]. Therefore, thinning may be an appropriate management response in some areas, such as where fire risk is particularly high (Burrows et al. 2022). Whether retained trees are harvested later or not can be determined as part of future planning processes[41].

However, the effectiveness of this approach may vary between forest types[21] and opening the canopy increases solar radiation on the ground which may increase fire risk. A more open canopy may also promote a denser understorey which would be prone to burn[21]. There are also arguments that the residues from thinning forests may increase fire risk in the short-term[11], although residues could be mulched or extracted for biofuels to reduce this risk.

Researchers differ in whether they think the overall benefits from thinning outweigh the negatives or not.

It has been postulated that combining thinning and burning can also serve to reduce future wildfire severity in certain forest stands (Keenan et al. 2021), although more research is needed to confirm this hypothesis.

Sow less seed

To avoid active thinning and the potential issue of increased residue, reduced eucalypt seeding rates could be used to reduce stocking rates and accelerate tree growth and thus resilience to wildfire[46]. However, this may come with negative implications for natural selection and tree form.

Incorporate green fire breaks

Adjusting the design of plantations and their management to improve fire prevention may include creating green fire breaks across the production landscapes. Green fire breaks are expected to help reduce the severity and spread of fires[13]. These breaks could be non-forested fire breaks, slow growing species with low flammability (e.g. blackwood), or even agricultural land. The common theme of green fire breaks is that they reduce fuels while maintaining habitats and corridors for a variety of plants and animals (Kelly et al. 2020).

Improve detection of bushfires

Early detection of wildfire could have important implications for the effectiveness of firefighting efforts. Investing in bushfire detection monitoring systems, using remote sensors and cameras could be a cost-effective measure[48].

Improve firefighting capacity and techniques

Having an effective and rapid firefighting response will help prevent large scale wildfires from establishing. Wildfires may increasingly occur in remote areas, due to greater incidence of lightning strikes (see above), so firefighting capacity needs to evolve with the changing nature of wildfires. In order to do this, adequate resources need to be made available[17].

Firefighting measures include standard practices such as manipulations of fuel. But at some stage fuel manipulation becomes redundant and other options are required such as fire suppression and fire retardant[13]. A clear framework for fire management options is needed.

However, the measures adopted during firefighting, including equipment used, can sometimes cause avoidable damage to other values including biodiversity and timber resources[25]. Developing response measures in advance to minimise the negative impacts of firefighting actions on these values is important.

Have one coordinated firefighting organisation

Another component of effective firefighting is the organisational structure. Currently there are three organisations involved in firefighting, and coordination and it has been proposed that efficiency may be improved by having a single bushfire and planned burn management agency[31]. Although there may be benefits in the diversity of approaches that different land management agencies can bring[50]. If multiple agencies are maintained, continued inter-departmental liaison especially in emergency response is important[25].

Maintain roads for firefighting

For efficient and effective firefighting, access is crucial. In the production landscape it may be prudent to maintain roads, track and fire breaks, particularly around plantations in high risk areas[48].

Do nothing

The option of doing nothing has been argued specifically for wildfires: that no effort should be made to control fires unless they are threatening important values. Many plants in Australia are adapted to fire and having a multi-age forest stand will promote resilience. Continually supressing fires may in fact create a bigger risk for the future[13], and heatwaves without fire could result in landscape scale mortality of eucalypts that are replaced by non-eucalypt forest types.

The option of 'do nothing' or maintain the existing state of affairs has also been proposed as a more general approach to climate change. It has been argued that climate change is so rapid that any actions taken are likely to be futile[32]. Furthermore all options are so full of uncertainty it is hard to justify a particular option. However some of the proposed adaptation strategies have benefits for other reasons than just climate change, such as improving catchment management or biodiversity in general, so may be worth considering even outside of the climate change discussion[34].

7.2.2. Improve forest resilience

If future fire regimes in Tasmania result in larger areas of forest being burnt, particularly by high severity fire, one of the key actions forest managers can undertake is building resilience into those forest types so that when the inevitable fire does occur, forest values are less impacted[41].

Maintain a multi-age forest

Generally, larger trees (in terms of diameter of the stem) are more resistant to the impacts of fire, owing to the development of protective mechanisms such as thicker bark (Clarke et al. 2013). The greater resistance of larger trees to fire impacts has been demonstrated in Victoria in dry eucalypt forest types, where larger diameter stems are more likely to reliably resprout epicormically (Fairman et al. 2019). In wet eucalypt forest types, even fire sensitive trees are more likely to survive fire when they have a larger stem diameter (Trouvé et al. 2021) [41]. Maintaining large old trees will also help maintain a source of seed into the future. Multi-age forest can be maintained at large and/or small spatial scales.

Limit forestry operations in a landscape

Forestry operations may impact fire proneness in a couple of ways. Residue left on the ground after harvest may increase short-term fire risk. Younger trees can also be more prone to drying out than mature trees, with associated increased potential fire risk. Limiting the amount of young forest (under 20 years old?) in the landscape may help minimise fire risk, although this measure is unlikely to make much difference under extreme conditions[13].

Shorter rotations

Shorter rotations may provide more opportunity for natural or artificial selection of tree species or genetic stock in the face of a rapidly changing climate[8,38]. Shorter rotations would mean opportunities to obtain forest products before the trees are fire killed or damaged.

However, shorter rotations combined with the increased fire frequency would further reduce the proportion of older forest classes in the landscape, exacerbating impacts on species of plants and animals associated with older forests. Also, larger trees are more able to survive fire impacts, so shorter harvest rotations could lead to reduced resilience to wildfire at the landscape scale[46].

Reduce clearfall operations

Clearfelling silviculture creates a uniform, singular age forest stand (although it is acknowledged that forestry operations operate under Code requirements that result in forest retention across the landscape for a range of reasons, Munks et al. 2020). Large trees are more likely to survive fire, and heterogeneous, multi-age stands are likely to be more resilient to climate change and wildfire[3]. Given the importance of large trees in a fire-prone landscape, it may be appropriate to implement silvicultural practices that maintain some forest canopy post-harvest, mimicking the kind of natural fires one would have historically seen in wet forests (Turner et al. 2009)[19]. Variable retention and other partial harvesting systems could be used instead of clearfelling, which would increase the probability of the more mature trees surviving and/or providing seed and a suitable microclimatic environment for regeneration of the site after wildfire[46].

Large clearfall operations can also affect the abundance and diversity of the understorey, which is a key factor in driving bushfire risk in wet forests. The flammability of wet forests is to a large degree dictated by the composition, density and structural diversity of the understorey (Kovácks et al. 2017, Norris et al. 2012, Cawson et al. 2017). The combustion of understorey trees and shrubs makes a crown fire more likely. Yet the understorey trees and shrubs also maintain the moist microclimate that historically made fire so rare in wet forests (Furlaud et al. 2021a). Future management of Tasmanian forests should carefully consider impacts on the understorey, as this is the one of the most important fuels from a fire behaviour perspective.

The forest industry in the United States, and specifically the US Forest Service, employs numerous silvicultural techniques that focus on the understorey in an effort to reduce fire risk (among other goals, including restoring ecological integrity and producing revenue from the sale of saw logs). These include a variety of types of thinning, selection harvesting, and shelterwood harvesting (Jain et al. 2012, Carey 2003), among others. Similar management techniques have been identified in Australia, include dispersed retention harvesting which was trialled at the WARRA Silvicultural Systems Trial.

Sow or plant alternative climate-suitable species or provenances

The selection of species or seed provenances that are more resilient to bushfire may facilitate greater ecosystem function and forest resilience in both plantation and native forests[48]. However, this comes with risk for other forest values (see Section 6.2.1).

Sow a diverse array of understorey species

As outlined above, one of the key features that impacts forest fire behaviour is the type and arrangement of fuels, including the understorey. Managing the understorey seems to be a significant factor from a fire behaviour perspective[19]. Sowing understorey seed may be one option for reducing the extent or severity of fire.

7.2.3. Promote improved post-fire recovery

Preparation for post-fire forest restoration work is very important should the interval between large fires begin to be 'squeezed' (Enright et al. 2015).

Increase seed storage capacity for re-seeding after fire

Sustainable Timber Tasmania (STT) currently have seed stores for *Eucalyptus* seed, but these may prove insufficient in the face of repeated extensive fires if regenerating eucalypts are not reproductively mature when these large fires occur. Building seed/spore stores for other vulnerable vegetation components such as understorey species would also be worthwhile (Ferguson 2011; Bassett et al. 2015) [41,46, 48].

Obtaining seed is complex so increasing seed reserves may be difficult[8,38]. Seed production is cyclical: flowering is abundant in some years and poor in others and can vary between locality and individual eucalypt species each season. The availability of seed therefore depends on the species and the season. For sowing operations, stored eucalypt seed has a shelf life of about ten years, declining in viability over time. STT are trialling a flower promoting hormone to potentially increase seed production (Williams pers comm).

Prepare post-disturbance harvesting prescriptions

The Code definition of a salvage operation is 'salvage operations involve forest practices which are not technically permitted by [the] Code but are desirable to achieve good long-term environmental outcomes by minimising potential or existing adverse environmental impacts and ensuring long-term forest cover on the site (*Forest Practices Code* 2020). In relation to salvage harvesting the Code states that the CFPO may provide alternative prescriptions on a case-by-case basis.

The rate of post-disturbance logging in Tasmania is expected to increase dramatically in the future under a changing climate. Clear policies/regulations for harvesting areas impacted by wildfire or some other agent (e.g. windthrow, dieback) would help the industry adapt to more fire-killed stands being available for harvest. These guidelines should provide clear guidance and expectations to industry, and clarity around how the recovery of biodiversity and ecosystem values will be managed and protected post-fire. These policies and regulations relating to post-disturbance harvesting should ideally consider the full range of potential fire sizes and severities to ensure they are meaningful for both moderate and very large, severe fires. For example, the scale of the 2019–20 bushfires in Victoria generated uncertainty about the suitability of existing prescriptions (DEPI 2014) and the impacts of the fire on forest-dependent threatened species, resulting in a greater reliance on the precautionary principle to manage values during subsequent harvesting (VicForests 2020; DELWP 2021). Post-disturbance harvesting policies and prescriptions developed with the worst (largest and most severe) landscape fires in mind[41,46,48]. To inform implementation of any such policies it is necessary to have baseline information such as fire severity mapping, understanding of the values as risk from post-disturbance logging, and mapping of fire refugia[34].

7.2.4. Protect important values

Identify at-risk values

Identifying at-risk values and developing widely-available maps and a database of these would facilitate better protection of important values during firefighting (some action is being done in this space by Emergency GIS[50]). As a next step, developing a clear process for prioritising important values would help ensure protection where required, for instances when firefighting resources are over-stretched[46]. A prioritisation process could be done, that considers the important values, their exposure to future climate, and their capacity to adapt (e.g. a ‘Markov vulnerability assessment’). TFS/DPIPWE should be consulted to confirm whether planned forest practices occur in high bushfire risk areas and may warrant additional fire management planning as part of the FPP planning process. Some values have already been identified and they could be incorporated into existing databases and decision tools.

Important values could include:

- threatened species/genetic resources at risk from wildfire
- important habitats or landscape features
- archaeological sites
- priority vegetation communities
- giant trees
- sites of geomorphological interest including karst areas
- research sites.

Some values, such as tree hollows, may be identified as important features to survey for after wildfire to see if artificial measures need to be introduced. Scenario planning could help identify when intervention is required[13].

Species with small range boundaries may be particularly vulnerable to the impacts of climate change so identifying actions that could be implemented to reduce the impacts on these species are important[13].

Reserve areas of old forest and vulnerable forest communities

Some vegetation communities and habitat features (e.g. old-growth trees with hollows) provide important values and can be at risk from wildfire. Older stands are typically less susceptible to wildfire so increasing reservation/retention of these important values may help maintain them into the future[18].

Improve protection of damp/cool refugia and riparian zones

Damp and cool areas, such as gullies, riparian zones, south-facing slopes etc, are likely to burn less frequently or at lower intensity so may provide important refugia for a range of values, including biodiversity. Modelling is required to identify likely fire refugia, and better protection of these areas, and improving connectivity of these refugia, may help maintain biodiversity under future fire conditions[32].

7.2.5. Adjust industry expectations

Include bushfire-related loss in timber modelling

It is important that bushfire-related losses and reduced production are incorporated into calculations of timber stocks and possible yields[31].

7.3. Research needs

One respondent noted that while understandings of interactions of timber harvesting and fire remain controversial and more research is needed, we probably have sufficient information to implement some of the constructive actions listed above[31].

7.3.1. Forest monitoring

- Good empirical data are needed. This will help the industry determine where and when to apply adaptive measures. It is important to monitor the important values so we have a way of assessing the impact both of climate change and adaptive actions. DELP in Victoria started to monitor a number of surrogates to assess the impact of fire (e.g. populations of plants and animals). A strategic assessment would be required to prioritise values (species, communities, forest health, soils, soil carbon, soil moisture, soil biota) we need to know more about[13].

7.3.2. Climate vulnerability/response

More information on the factors that influence if and how the forests burn

- Under what conditions do the live understorey species of wet sclerophyll and mixed forests become dry enough to burn (and hence allow for the development of crown fires). Almost no research has been done in this area other than by Dickinson and Kirkpatrick (1985).
- Understanding how climate change will affect plant flammability and the vulnerability of Tasmania's wet forests to an increasing frequency of crown fires[19].
- More work on soil moisture measurement for fire management purposes[39].
- Trying to understand the feedback loop between fire frequency and forest structure and what that does for promoting fire frequency[21].
- Synthesise western and Aboriginal knowledge of how the Tasmanian landscape and indigenous land management has changed in relation to past climate-change.

- How susceptible to wildfire particular areas in the forested landscape are expected to be needs to be mapped/predicted and made available to relevant agencies. This information can then be used in a risk assessment to inform decisions on when to recommence harvesting in wildfire impacted areas.
- Identify what factors contribute to a step-change in bushfire risk, and ways to monitor these so adaptive management practices can be put in place as appropriate. This will differ depending on vegetation environmental sensitivity and projected changes to rainfall, soil moisture and evapotranspiration, extreme temperature[6].

More information of the factors that affect regeneration

- Identify areas that are most 'at risk' from changing fire regimes[34].
- The impacts of repeated fires on ecological communities[46] and the factors that influence resilience.
- What are the allowable inter-fire intervals to prevent ecological collapse (taking into account fire severity)? (See recent work by Leonard, 2021).
- Vulnerability of Tasmanian forest ecosystems to changes in fire regimes, and how this can then be incorporated into forest practices[41].
- Determine if plant species are likely to keep up with changes in climate and fire. That is, can some species adapt fast enough to keep up with the pace and magnitude of environmental change? (For examples see work by Luke Kelly, such as Senior et al, 2021).

Research into the species/provenances that are more fire tolerant

- If there are species or provenances that are particularly vulnerable to climate change induced fire regimes, then at some point in the future it might prove necessary to sow seed from other species or provenances to regenerate sites back to eucalypt forest. Setting up additional species and provenance trials for a wide range of tree species in a variety of altitudes would be worthwhile[46].
- Research on identification of fire-tolerant/more resilient eucalypt species.
- More work on identifying wildfire refugia, in order to protect these areas[34].

Better understanding of the role of timber harvesting in fire patterns

- Examine how bushfire risk is influenced by current forest practices such as landscape-scale configuration of various forest growth stages[31].

7.3.3. Effectiveness of adaptation options

Forest thinning

- Research on the role of ecological thinning silviculture in reducing bushfire risk (Patrick Baker's research, e.g. Burrows et al. 2002).
- Environmental impacts of forest thinning on variety of ecosystem values (i.e. other than the benefits to overstorey trees) [41].
- Ecological thinning approaches in diverse forest ecosystems[41].
- Impact of increase in thinning on resource availability[41].

- The impact (positive and negative) of combining thinning and burning to reduce future wildfire severity in certain forest stands (Keenan et al. 2021). These concepts, particularly relating to management of dry forest types under climate change and the combination of thinning and prescribed fire to mitigate future fire impacts, are currently being explored in the west of the United States (Stephens et al. 2020) [41].
- The cost-effectiveness of non-commercial thinning and fuel reduction operations compared to the economic costs of bushfires (control and recovery).

Salvage harvest

- Ecological impacts of salvage harvesting in Tasmania and how to effectively mitigate these with best practice salvage harvest prescriptions and exclusion zones, with particular consideration of megafires[41,46].

Fuel manipulation

- We need to better understand the conditions under which manipulations of fuel does not become important because fire severity is too high[13].
- Model the fire risk based on fuel profiles, e.g. in conjunction with thinning trials and measurements of fuel loads and how these change over time.

Planned burns

- Consult with experts on indigenous land management/cultural-burning practices.

Firefighting

- Explore the most efficient firefighting configuration of machinery and personnel in relation to fire location, severity and size[25] (noting some work has been done in this area[50]).
- How to effectively reduce fire risk and manage fires when they do occur[46].
- More research into fire behaviour, fuel hazard, fuel moisture and soil moisture would be nice. However the level of knowledge in this area is not currently a major limitation[17].

8. Soils

8.1. Potential impacts

8.1.1. Increased erosion

Greater frequency of extreme rainfall and fire could increase soil erosion

Higher temperatures are leading to a greater frequency of intense short-term rainfall[1], which can increase soil erosion and debris flow risks[1, 4, 34]. Particularly if the high rainfall coincides with recent forest harvest (Slee and McIntosh, 2022). Severe drought can also increase forest fire risk and consequential risk of erosion by wind and runoff (Sharples 2011). Greater intensity of rainfall may also result in an increased risk of landslides in some areas and accelerated loss of some relict soft sediment deposits and landforms (Sharples 2011).

Fires also enhance erosion risks and post-fire debris flows in southeast Australia can be 2–3 orders of magnitude higher than background erosion rates from undisturbed forest (Nyman et al. 2015). The degree of post-fire debris flow varies with burn severity and rainfall intensity and between landscapes, and is more likely to occur in drier forests (Nyman et al. 2015)

8.1.2. Changes in soil biota and function

Increased soil degradation

It has been predicted for the TWWHA that moorland organic soils will degrade with climate change due to seasonal drying, warming and fire, especially on better-drained slopes (Sharples 2011). Forest organic soils may also degrade due to increased warming, greater seasonal drying and increased fire risks (Sharples 2011).

Warmer conditions may change soil nutrient cycling

Because of warmer conditions (particularly at night) and more CO_2, the rate of soil processes such as decomposition and nutrient cycling are being increased. This is expected to remain the case provided there is adequate soil moisture, which is currently uncertain under climate change projections[12].

Increased fire frequency may affect soil nitrogen availability

The impact of fire on soil nitrogen is uncertain, as there are so many different microbial taxa involved (nitrifiers, denitrifiers, nitrate reducers, aerobic nitrate oxidisers etc). Fire generally decreases the abundance of nitrogen fixers, but this generalisation does not always apply to all taxa thought to fix nitrogen. Therefore while we know that fire *may* impact soil nitrogen availability, there is great uncertainty as to how much or under what circumstances[20].

Changes in soil biota

The most immediate impacts of climate change on soil microbial communities will likely be related to elevated temperatures, drought and the predicted increases in wildfire frequency and severity[20], and changes in soil moisture[4]. Soil microbial communities respond rapidly to environmental change and are very well dispersed, so it is likely that they are already being impacted by these factors over large spatial scales. However, they also exist in an extremely heterogenous environment, so it is possible that impacted communities will be in relatively close proximity to non-impacted communities, providing potential paths for rapid recolonisation and recovery[20].

The long-term impacts of elevated temperatures and increased fire frequency and severity are harder to predict for soil microbes, as these will likely be driven by how above-ground communities are impacted by these factors, especially for symbiotic species[20]. However at some point changes in soil biota can/will impact ecological function[4].

Decrease in soil nutrients

Increased fire severity will likely lead to more carbon loss from Tasmanian forest soils. Fire causes microbial death, depleting soil carbon pools previously tied up in microbial biomass, with increasing fire severity leading to greater microbial mortality. Further, fire disturbance leads to the predominance of decomposers over symbiotes in soil communities. These decomposers break down organic matter in the soil, releasing CO_2 into the atmosphere. The rate of decomposition also increases with elevated temperatures, potentially exacerbating this effect[20].

Fire also helps to break down stable soil organic matter (clay complexes) leading to nutrient leaching and clay eluviation and (in the long term) to development of texture-contrast soils which support fire-tolerant (dry) forest types (McIntosh et al. 2005).

Reduction in abundance of mycorrhizal fungi

High intensity fires can reduce the abundance of mycorrhizal fungi in the soil, with these impacts persisting for 10–20 years post-fire. These fungi are important for the establishment and survival of tree species (including *Eucalyptus* spp.) and plant uptake of soil phosphorus. Mycorrhizal communities have also been shown to help plant communities survive droughts (as they increase a plant's water uptake ability). With increasing fire frequency and severity, it is likely that mycorrhizal fungal communities will not have enough time between fires to recover sufficiently. This may result in reduced regeneration and survival of tree species in Tasmanian forests[20].

8.2. Potential adaptation strategies

8.2.1. Review measures used to minimise sediment movement

Increased intensity of rainfall, particularly when combined with wildfire, is likely to increase the likelihood of sediment movement. Current management measures were developed with historic rainfall patterns in mind and will need to be reviewed to ensure they can accommodate the effects of intense rainfall. For example, the spacing of grips used on extraction tracks and culverts, culvert pipe diameters, riparian streamside reserve widths, quality of road surfaces, and road drainage design, may need modifying.

As part of these considerations it will be important to periodically review new machinery/technology in the Code, matching soils and slopes for harvesting, roading and land preparation[44].

8.2.2. Reduce incidence or intensity of fire

Take measures to reduce wildfire risk – burning, thinning, firebreaks

Reducing wildfire risk via fuel reduction burning, thinning and management of appropriate firebreaks[20].

Ensure non-uniform distribution of fuels across harvest site

Altering the distribution of fuels across a harvested site to avoid uniform, high-intensity burns and promote lower-intensity mosaic burns would help promote community recovery from less impacted soils nearby[20]. This would need to be balanced with the distribution and occurrence of a suitable seed bed for eucalypt regeneration[2].

8.2.3. Improve forest resilience

Retain mature elements within harvest area

Retaining mature elements within harvested areas. i.e. ‘seed trees’, facilitates recolonisation of mycorrhizal fungi into burnt areas[20].

Reduce clearfall operations

Alternative forms of silviculture, such as aggregated retention, are good for providing spores of soil biota and above-ground plants that are needed to maintain soil biota[12] and are a way of creating a fine-scale heterogeneous landscape. However the practicalities of this would need to be carefully approached to ensure adequate regeneration was achieved.

8.2.4. Promote improved post-fire recovery

Inoculate the soil with mycorrhizal fungi

Consider supplemental planting of tree species with mycorrhizal fungal associations to reintroduce intact plant-fungi symbiosis into disturbed environments where required[20].

8.3. Research needs

8.3.1. Forest monitoring

The potential impacts of climate change on soil microbial communities are poorly understood due to the complexity of the soil environment and multitude of feedbacks with above-ground processes[20].

8.3.2. Climate vulnerability

Conduct research on the impact on soils of climate change e.g. increased erosion potential, particularly effects on high-erodibility soils, landslides, karst development, soil carbon in response to increased frequency of climate extremes[44].

9. Water

9.1. Potential impacts

9.1.1. Increased water stress on forest

Increased tree mortality

Water stress in Tasmanian forests is likely to increase under climate change. Rainfall patterns are becoming more variable, with greater chance of severe drought[25], resulting in widespread tree mortality, with some species being more susceptible than others. Drought can result in lower regeneration establishment and performance in those times, and also greater risk of bushfire.

The occasional wet year will be crucial to the health of the forests. Many trees will rely on deep water stores so can sustain themselves in dry years, but it is hard for plants to use these deep stores. Our understanding of ground water systems is limited[21], but deeper reservoirs are expected to be associated with particular forest types to an extent [44].

Change in forest structure

There is likely to be some change in forest structure under climate change, as stands will self-thin if too stressed and some species/genotypes will respond better than others[21].

9.1.2. Stream health

Changes in stream flow

Rainfall intensity is projected to increase across Tasmania, with longer dry periods in between heavy downpours. A project was done that projected future catchment yields for Tasmania for more than 1900 sub catchments in 78 river catchments (>70% of the state by area) (Bennett et al. 2010). They found that on average state-wide annual runoff is likely to increase with the effects of climate change. Annual runoff is likely to decrease in the central highlands, increase in eastern areas and the Derwent valley and South Esk river and lower Macquarie River. West coast runoff is likely to increase in winter and decrease markedly in summer and autumn. Of the 78 rivers modelled, on average 32 are projected to have changes in mean annual flows of more than 10% by 2100. On average, 28 of the 78 rivers modelled are projected to have decreased flows by 2100, while 50 rivers are projected to have increased flows. However, in one climate projection as many as 55 of 78 rivers have decreased flows, while in another climate projection 77 of 78 rivers will have increased flows (Bennett et al. 2010).

Available models of forest water use over time are limited, and mostly relate to the ‘ash’ species. Young trees are likely to use more water than older trees, but in non-ash species this is not likely to be by much or for very long[21]. This means that while stand age, changes in fire and vegetation may have some impact on stream flow, in most forest types in Australia stream flow will be largely driven by rainfall patterns[4, 21]. Climate change also has the potential to reduce stream flows during the extended dry periods, most noticeably in headwater streams[15]. Gradual change in runoff have been predicted for Tasmania, with estimates of 10–20% reduction by 2030/2100 (Tas SY and Climate Futures[14])

Less consistency of catchment-wide water balance and temperature interactions means there is the potential for forestry activities to have an increased impact on environmental flows and downstream water availability. (Although the impact of forest management on stream flows should be considered in the context of other land uses such as agriculture and urban development[2]). Given the increasing magnitude of extremes in rainfall at both ends of the scale this raises the possibility of rapidly growing young forests taking a greater per cent of the flow or conversely, if recent harvesting operations coincide with extreme rainfall then runoff and erosion could increase[28]. The risk of this occurring may be mitigated to an extent by establishing streamside reserves of planted or seeded native vegetation (Slee and McIntosh, 2022).

Increased stream temperatures

Climate change is likely to result in increased water temperatures, impacting on the survival of headwater stream-dwelling species[15].

9.2. Potential adaptation strategies

9.2.1. Improve forest resilience

Forest thinning

Thinning a forest can temporarily reduce overall evapotranspiration and increase water availability for individual trees[25], thereby increasing water availability, improving resistance to drought, increasing growth rates and consequently increasing resistance to fire (Burrows et al. 2022)[21]. However such effects will most likely last only 2–3 years (although depending to some extent on the rate of thinning, see Hawthorne et al. 2013), varying with forest type, rainfall occurrence and the season of thinning. This is particularly the case for *E. delegatensis* forests. Thinning forests can be logistically challenging, and can create safety concerns, so is unlikely to be a widely used tool in some forest types, but could be used as a management tool in key areas during times of need (e.g. droughts) [21].

Changes to regeneration regimes to ensure reforestation

Careful consideration will be needed of when it is best to restock by planting or seeding, as survival can be low during drought[14]. Reduced stocking of plantations and native forest may also be required to account for drier conditions[21].

9.2.2. Minimise disturbance within catchments

Limit harvesting within a catchment

The amount of harvesting in a catchment affects stream flow and water supply (Vertessy et al. 1996)[21], initially increasing flows (due to the absence of trees which reduces transpiration losses) and subsequently reducing flows as the rapidly growing young trees transpire (Vertessy et al. 2003). In a mass regeneration event any rain that occurs will go more to the soil and plants than to streamflow, particularly if water levels are low[21]. Effects can be moderated to an extent by careful planning (Vertessy et al. 2003). The adequacy of the coupe dispersal provisions in the Code should be reviewed to determine if they are adequate for maintaining streamflow in a drying landscape, particularly in the headwaters[6].

Coordinate catchment management

To achieve catchment-level management there needs to be coordination between different companies and users to minimise effects of harvesting, roading etc[48]. This may be achieved by coordinating FPPs within catchment level with an emphasis on stream riparian protection and water yield[44]. Alternatively catchment-scale Vegetation Management Plans that require FPPs to comply with catchment protection provisions could be implemented at the operational scale[34].

Greater protection of high-risk catchments

A process should be undertaken to identify high-risk catchments, where increased soil and water protection measures should be implemented. These high-risk catchments may be more susceptible to reduced streamflow or contain values of high importance[48]. As high-risk coupes and small catchments are already identified on soil erodibility, slope and geomorphological criteria (e.g. presence of landslides) (see FP Code Tables 4 and 7 and related text), identification of high-risk catchments at a larger scale should not be problematic.

The Conservation of Freshwater Ecosystem Values (CFEV) layer does give an indication of conservation management priority, be it for ‘immediate priority’ or ‘potential or future priority’ (DPIPWE 2014). However, this assessment incorporates conservation value (naturalness and representativeness), condition and land tenure security rather than issues of erosion risk, land-use change and climate change specifically.

Increase coupe dispersal

Dispersing coupes will minimise the potential impacts of harvesting on a stream system. One recommendation put forward as part of the review of the biodiversity provisions of the *Forest Practices Code* suggested conserving a proportion of Class 4 stream catchments within any CFEV catchment (Barmuta 2008).

Smaller coupes

Smaller coupes will help reduce the local impacts of the harvest event on stream systems but the overall effect on water yield may be minimal if the number of coupes is increased to deliver the same timber yield.

9.2.3. Greater protection of important values

Widen riparian buffers

Retaining riparian zones performs several important functions[6]. It shades the streams to maintain stream temperatures, which is important for biota. They are places where trees are more likely to flourish in droughts and provide important refugia and connections for many fauna species. Finally, they also help maintain water quality[21]. However, the changes that are expected under climate change, including drought, may reduce the efficiency of current streamside reserves for protection of riparian values. A review of streamside reserve widths, especially in headwater streams and priority and high risk catchments, may be warranted in response to increasing demand on Tasmania’s water resources, combined with increasing temperatures (Barmuta, 2008)[6,23].

Improve roading in catchments at risk of flooding

Under climate change there may be a higher risk of flood in some catchments. A flood recurrence interval and road class table for high-risk catchments should be developed, and the requirements for road construction and maintenance should be upgraded for high-risk areas[48].

Culverts may need larger diameter pipes to cope with larger maximum flows, to prevent blockages such as those observed by Slee and McIntosh (2022).

9.3. Research needs

9.3.1. Effectiveness of adaptation options

- Research is needed on the role of ecological thinning in reducing soil and water disturbance in high risk catchments[48].
- More research is required to understand how best to manage catchments to maintain streamflow under a changing climate, although the level of knowledge we have is probably sufficient to begin to develop a strategy[34].
- Efficacy of current requirements of harvesting around headwater streams and of streamside reserves with regard to protection of aquatic and riparian values[6].

10. Biodiversity

10.1. Potential impacts

10.1.1. Change in vegetation communities

Drought (combined with elevated temperatures) can result in plant/tree mortality

Drought leads to cavitation stress in plants, leading to air bubbles in xylem vessels. In extreme cases this can lead to plant/tree death and widespread forest dieback in response to drought. Effects will be exacerbated by elevated temperatures, and potentially also by fire. The risk of mortality will vary with tree age as older trees with deeper roots are better able to access soil moisture as the surface soils dry out[46].

Tree death may result in a change in forest communities

Some species appear to be more susceptible to the impact of a changing climate than others (e.g. current dieback of *E. viminalis*). When there is substantial tree death it could result in a change in forest community[30]. Species associated with wetter forest communities are likely to be particularly impacted and these forests may shift to drier forest vegetation communities. Dry forest communities are also likely to become unsuitable habitat for certain species of plants and animals. It is possible that species that are currently relatively common could become rare or at threat of extinction[46].

Tree death or changes in forest community could result in loss of habitat for other taxa

Tree death can have flow-on effects on other taxa. For example a loss of canopy could detrimentally affect understorey and ground species[30]. Plant and animal species with restricted ranges and/or poorer dispersal abilities, or strong vegetation community associations, may be particularly at risk. Old-growth trees may die and not be replaced if trees are no longer able to survive for several hundred years. As a result, hollow-dependent vertebrates and saproxylic invertebrates and fungi associated with them may lose important habitat. An example of this process is the current high level of dieback of *E. viminalis* (known as ginger tree syndrome), which is likely to affect the conservation of the highly dependent and threatened forty-spotted pardalote[30].

Non-forest communities may also change extent, range, and composition over time

Not only would climate change potentially impact on the range and distribution of forest communities through changes in temperature, rainfall, weather extremes and ultimately fire, non-forest communities are likely to also be affected[50].

Compounding impact from forestry operations

There is likely to be significant habitat loss for many species, from bushfires, dieback etc. Forestry operations could cause additional loss for some species, so the losses from different disturbances are compounding[48]. High risk threatened species (e.g. galaxiids, swift parrot, aquatic fauna, snails, and stag beetles) are expected to be particularly at risk from these compounding effects[48]. Non-threatened species that depend on ‘at-risk’ habitats may also be of concern (e.g. cave fauna, hollow-using fauna, soil dwellers), as well as less mobile and restricted range species (e.g. Legge et al. 2020) [34.]

10.1.2. Widespread shifting or loss of ecological niches

The drying of freshwater systems could negatively impact biodiversity

The forest industry is required to consider and manage habitat for threatened species and other biodiversity values. Of the 119 invertebrate species currently listed as threatened, 69 are aquatic or require access to water to breathe; meaning that how catchments are managed is paramount for their continuity in the landscape[15].

Climate change has the potential to reduce stream flow in some catchments, most noticeably in headwater streams[15]. Flow regime changes alter the availability of habitat, both foraging and breeding, for aquatic biota and have the potential to greatly reduce area of occupancy of narrow-range endemics[34]. For species such as freshwater galaxias, a number of which are restricted to headwater streams above areas containing trout, any reduction in flow to streams currently supporting threatened fish may result in localised extinction[15].

The drying of streams and freshwater bodies could have negative consequences for terrestrial vertebrate and invertebrate animals that rely on them for water sources. For example, a decrease in the number of native hens on Maria Island compared to those recorded in historical records relates to drying of water bodies. Similar impacts would be expected for numerous species[46].

The warming of streams will alter habitat suitability for some species

Stream temperatures are rising[42], with the effect exacerbated where riparian vegetation is lacking. Headwater stream-dwelling species such as freshwater molluscs and species like *Astacopsis gouldi*, require cool (3–18°C) conditions in larger streams to successfully breed[15]. Under a changing climate therefore many streams may become increasingly hostile environments for their current inhabitants.

The microclimate under the forest canopy will change and affect the persistence of other species

To some extent the microclimate under the forest canopy may be buffered from the full effects of climate change by the forest canopy cover and understorey characteristics[18]. However changes to the microclimate will occur, to varying degrees.

There is likely to be considerable variability in how well species persist within a changed microclimate. Factors which may promote persistence in adverse climate may include resilience of the established mature plants to climate impacts combined with long lifespans or capacity to regenerate vegetatively. A lack of better-adapted plant species competing with existing species may also enable persistence[18].

Disturbance will alter species composition

Disturbance is likely to be a catalyst for species changes. For some species it may be positive, providing an opportunity for them to adapt by providing recruitment events that enable selection of traits better suited to the new climate regime. On the other hand, recovery of some plant species may fail following disturbance by wildfire/logging/salvage at sites where the local climate/weather following disturbance has changed beyond the tolerable climatic niche of the species, particularly if there is overwhelming competition from species better adapted to the new climate and disturbance[18].

Increased fire threat is likely to reduce habitat available for a number of range-limited fauna. This has been observed already on the Central Plateau where the habitat available for *Castiarina insculpta* has reduced by 50% in one fire event, while the absence of *Lissotes menalcas* from logs scorched by wildfire in 2019 has also been noted (Richards & Spencer unpubl. data) [15].

Species will vary in how vulnerable they are to climate change

Climate change has the potential to impact on the breeding cycle of many forest-related (and non-forest related) fauna, in particular the invertebrate fauna in wet forest types. Dry forest communities support a different suite of invertebrate fauna, many of which are adapted to dry conditions. It is unclear how reduced soil moisture and extended dry periods will impact such dry-forest species, but some changes are considered likely[15].

The species most likely to be impacted are those that combine traits of climatic-range restriction with disturbance sensitivity (e.g. some rainforest species dependent on high rainfall and cooler micro-climates and low tolerance to fire and short dispersal capacity). The least resilient species are likely to be those relying on re-establishment from seed, particularly species for which the seed source is not available within the site (e.g. species without an aerial or soil seed bank) [18].

In some cases, species may be able to shift their distributions to higher altitudes where conditions are typically cooler, but numerous species will have limited dispersal capacity[46].

Forest soils may dry out, with implications for soil-dwelling biota

Long periods of drought may restrict habitat availability for species with edaphic (soil-dwelling) life history stages. Drying soils have been recorded impacting on the presence of such species (e.g. *Hoplogonus bornemisszai*; Richards & Spencer, in prep). [15]

The decay rates of rotting wood may change, with implications for saproxylic species

Rotting wood supports a suite of invertebrate fauna and wood decay rates and rot types may be impacted by drying of forests, thus potentially impacting the presence of certain log-dwelling species such as *Lissotes menalcas* and Onychophoran species[15].

Species loss

All the combined impacts of climate change and other threats, such as modified fire patterns and introduced species, are already increasing the risk of species extinctions (Kelly et al. 2020), although predicting future extinction risks faced by individual species is harder to predict (e.g. Warren et al. 2018; Warren et al. 2021). For example, if a species is already threatened due to significant habitat loss, then an additional range reduction caused by climate or fire could be expected to have an amplified impact. Further, an increase in extreme events is likely to reduce numbers of most species, and species listed as threatened due to low numbers are likely to be at greater risk as a result. However, ecology is a complex science, and adaptation and evolution are powerful forces. If, for example, a competing species suffers a greater impact and declines in abundance, this reduction in competition may compensate for the direct negative impacts of climate change[5].

Change in food availability/nutrition

Climate change may result in a decline in the nutritional value of foliage for folivores (invertebrates and vertebrates), for example from lower moisture content and digestibility (see Lunney et al. 2012) [34]. This could result in changes in population densities, or distributions of fauna.

10.1.3. Changes in timing and efficiency of reproduction

Predicted impacts on biodiversity include changes in timing of breeding and flowering for large proportions of species (e.g. Parmesan & Yohe, 2003), including those which are widespread and common. It is also anticipated that these changes may occur at different rates for different, dependent species (e.g. Simmonds et al. 2020). For example, it is possible that pollinators' reproductive timing may be dependent on cumulative temperature, but plants dependent on them may synchronise the timing of their flowering by photoperiod[5]. This may reduce the effective pollination of plants, or resources available for breeding fauna (particularly those with specialised diets). See section 6.1.3 for further comment.

10.1.4. Increased prevalence of weeds, pests and disease

There is a chance that the prevalence of weeds, pests, and diseases including parasites will increase with climate change[23,27].

10.1.5. Loss of ecological function

The changes that will occur under climate change, including changes to flora and fauna populations, are anticipated to result in large-scale disruption of ecosystem functioning[5, 48]. Diverse systems are typically more resilient, so the stability and function of ecosystems may decrease as ecosystem diversity decreases. Some of these ecological functions are important to humans (e.g. soil conservation, water purification, crop pollination, food provision, tourism, amenity, and human wellbeing)[5].

10.2. Potential adaptation strategies

10.2.1. Improve forest resilience

Sow seed for climate-suitable provenances

Sowing provenances with adaptations to the new climate regimes may become necessary to maintain ecological function. Initiating species/provenance trials now in a range of locations is recommended. The early establishment phase might be particularly challenging in a hotter, drier, more fire-prone environment[46].

Increase habitat connectivity

Increasing connectivity between forest areas may allow species unable to persist in certain conditions to access to more favourable ones[5].

Widen riparian reserves

Riparian areas can provide habitat for biota and are typically less likely to be severely burnt. Widening riparian buffers will therefore provide more habitat for biodiversity as well as helping provide linkages between undisturbed areas[5, 15, 18, 42]. Wider streamside reserves may also help maintain the cooler conditions that some aquatic species are reliant upon. In areas where riparian vegetation is lacking, revegetation programs should be implemented.

Apply forest thinning

Thinning has the potential to reduce drought stress mortality and increase survival rates in wildfires. However, it may come at the risk of temporarily increased fuel loads and fire risk. Alternatively seeding rates could be reduced after harvest to reduce tree stocking and increase tree resilience to drought and fire[46], thereby avoiding any potential increase in fuel loads. However the full implications of lowering seeding rates are uncertain, and argued against by other researchers (see 6.2).

Limit harvesting within a catchment

Minimising the proportion of a catchment that is disturbed will help maintain the integrity of the catchment and thereby streamflow.

Implement green fire breaks

Implementing green fire breaks could help reduce fire risk, and if done carefully could facilitate fauna movements and maintain habitat connectivity. However, implementation would need to be considered carefully, particularly in the choice of species used to ensure there is no risk of them becoming invasive weeds[46]. If the green fire break was comprised of non-forest, the carbon and biodiversity impacts of clearing vegetation would need to be carefully considered[2].

Adjust timing and scale of planned burns

The timing of planned burns (regeneration or ecological) may need to be revised to minimise impact on biota[15]. It is important to ensure that some burns are conducted on a small scale to ensure patchy retention of habitat for some species such as small mammals[9].

10.2.2. Reduce intensity of forestry

Maintain heterogeneous landscape – smaller and dispersed coupes

Strategically managing disturbance regimes such as harvesting will be important for maintaining a heterogeneous landscape, that is more likely to capture the requirements of more taxa. This will allow some areas to have longer intervals between disturbance to meet species requirements[18]. Dispersing coupes would give biota more time to disperse or colonise the disturbed area. However, unless wood volume quotas are adjusted the impact of increased coupe dispersal across the production estate would need to be carefully considered.

Adjust rotation lengths

Given the diverse needs of native biota, the full range of forest ages are needed to maintain biodiversity. Currently there are recommended intervals between forest harvest operations. In some areas rotation intervals may need to be reduced. For disturbance tolerant species in native forest, enabling disturbance events to occur more frequently than usual will provide more recruitment events enabling greater opportunity for genetic adaptation to the new climate within a site[18].

However, in other areas disturbance intervals must be longer than currently implemented for other species to reach full reproductive productivity or to maintain disturbance sensitive species[18]. High disturbance frequencies and intensities are more likely to result in more immediate species losses of disturbance sensitive species[18]. Lengthening the rotation time may be particularly important to maintain species marginally maladapted to the new climate, enabling opportunities for genetic adaptation as well as to extend the time available for species to disperse into new areas where they may be better adapted[18].

Smaller coupe sizes

Constraining the area or pattern of disturbance may help mitigate climate change impacts by retaining older trees more likely to survive and minimising the increased temperatures and soil evaporation that occurs in cleared areas[15, 18]. (See Section 9.2.2 for further comment).

Apply different silviculture

There are a range of known silvicultural techniques that could be used instead of clearfall silviculture. For example, narrow strip harvesting or aggregated retention maintain structures such as canopy shelter. This will help recruit a diversity of taxa (good for forest resilience), reduce solar radiation and temperatures of disturbed ground[15,18] which will help regeneration.

Alternative forms of silviculture could also target retention of other features known to maintain humidity in the understorey, such as treeferns, epiphytes and cryptogams[18].

Silvicultural methods used should be selected in response to the change in climate being experienced at a site. For example, the methods identified might vary for locations where the predicted change in climate is for an increased length or frequency of drought or increased magnitude or frequency of extreme heat days, compared to locations where the change is likely to be an increase in rainfall[18]. However, a strong adaptive management approach would be needed to implement an adequately responsive system.

Apply different regeneration methods

A number of respondents noted that instead of continued use of high intensity burning, alternative post-harvest forest regeneration techniques should be explored[15+].

Reduce fuel loads by utilising more residue

There is likely to be a reduced window for regeneration burning as a result of climate change. This combined with the impetus to retain old-growth trees may provide incentive for alternative fuel management techniques such as using harvesting debris for biofuels and relying on mechanical disturbance for site preparation. It should be recognised that this will come at an ecological cost to species and ecosystem processes adapted to periodic wildfire, and thus wherever practical regeneration burning is still recommended even if it involves burning piles rather than broadcast burns. Regeneration burning changes the nutrient composition and microbial communities of the surface soils (Ammitzboll et al. 2021, 2022) and stimulates germination of seeds of understorey plant species from the soil seed bank (Hindrum et al. 2012) [46].

10.2.3. Protect important values

Register priority areas

To manage a value adequately, there needs to be a good understanding of what those values are and where they occur. This means a widely available register of priority areas is needed (e.g. at risk vegetation communities or giant trees). These registers can be used by multiple users, from guiding harvest operations to firefighting and planned burns[46]. For these we need a good understanding of the communities most at risk from climate change[48]. Some of this information is already available, but should be reviewed to ensure it is comprehensive and available to all relevant users.

Increased reservation/retention of at-risk values

It may be appropriate to reserve at-risk values if timber harvesting is likely to compound risks associated with climate change (e.g. old-growth and mixed eucalypt/rainforest vegetation types; areas that are likely to be relatively fire or drought resistant based on topography) [46]. There may also be need for greater retention of threatened species habitat to account for the future risks posed by climate change[48]. For example, areas that provide refugia for palaeoendemic flora over past current and future climates may be prioritised for management (Mokany et al. 2016). Also of great importance is managing habitat for native pollinators[15].

Restore cleared lands

Restoring cleared lands, such as riparian zones or unused agricultural land, will increase the amount of habitat available for biota[34].

Maintain climate refugia and seed source patches

There should be strategic conservation of climate refugia for important species and vegetation types as well as forest patches that are located in fire resilient refugia within the landscape.

For species least resilient to climate change, areas of seed thought to be adapted to future climates should be retained to act as future seed sources[8]. This may assist persistence of some species and enhance their opportunity to spread to more climatically suitable areas (e.g. Andrus et al. 2021)[18].

Improved protection of retained features

There should be better protection of values retained from harvesting, such as streamside reserves, habitat clumps and other excluded areas from regeneration burns[15]. This should include areas retained at a landscape scale, particularly in high-risk bushfire areas (e.g. rainforest communities or mature wet forests with rainforest understorey) [48]. This protection may involve greater fuel management at the harvest boundary to help ensure the areas are not impacted by planned burns. Or it may involve implementing fire breaks between highly flammable areas (potentially plantations for example) and high value and sensitive intact forest[45].

Minimise deforestation

The commonest threat to species is habitat loss and modification or, more generally, unnatural rates of change. Efforts to avoid removal of native habitat and ideally improve and restore native habitat across Tasmania should result in larger populations of many species. Clearly this general approach will also achieve the additional, highly desirable conservation outcomes of retaining and increasing intact, functional ecosystems, and reducing carbon emissions[5].

Ensuring there are practical and equitable management recommendations that prescribe minimum levels of habitat to be retained in landscapes with remnant/degraded habitat would be extremely valuable[48]. Ceasing clearing or harvesting of poorly reserved RFA communities on private lands should also be prioritised[46].

Facilitate expansion/recruitment of habitat for threatened species

For some species, recruitment/restoration of habitat may be appropriate. This may need to occur outside their historic range, in areas where that will be suitable under a future climate[48].

In some instances this may merely be addressing barriers to movement (e.g. creating vegetation corridors in a fragmented landscape[48].

Facilitate species translocations

In the longer run it might be necessary to at least consider facilitating species range shifts, although this would come at considerable risk to the species if numbers are extremely low so should be a last resort[46]. If it is considered desirable to actively translocate species into new areas, then the best time for this to take place is likely to be post-disturbance. This may be of relevance for the preservation of threatened species. Translocation of species or species genotypes should only be undertaken after consideration of all the likely issues involved. Methods for translocation of species or genotypes could include aerial dispersal of seed, planting of seed, seedlings or plants depending on the ecology of the species and biosecurity concerns. Experiments should be conducted as an initial trial, and post-translocation monitoring is recommended. Browsing protection measures may be initially required in some circumstances[18].

Increase efforts to reduce other threats on biodiversity to increase resilience

In terms of species which are threatened or near-threatened, the overall advice is to re-double efforts to reduce current threats, to boost overall resilience. More generally, there are likely to be many other species that become newly threatened by climate change, and all possible efforts to minimise additional potential disturbance to natural processes are recommended[5].

Triage species management

As climate changes, some species will be outside their climatic envelope or other circumstances (e.g. predators or disease) may make their ongoing persistence unlikely. Given limited resources and a changing environment a point may be reached where it is no longer sensible to try and maintain such systems/species in the Tasmanian landscape[29].

10.2.4. Improve capacity to adapt to change

Apply adaptive management

To maximise knowledge gain and responsiveness to future conditions, forests should be managed as ‘complex adaptive systems’. Adaptive management involves learning by doing and having a clear process for testing alternative actions and monitoring outcomes to improve future land use. To do this a range of silvicultural approaches should be trialled within an adaptive management framework[46].

Have a flexible, multi-scaled and responsive management system

Measures to mitigate the interaction effects of disturbance and climate changes could be strategically implemented either where threatened species are at risk of further range and population reductions or in areas where there is a high likelihood of rapid localised extinction events of species considered more common (e.g. areas where a high number of species are on the margins of their climatic range) [18]. Multiple different disturbance could be impacting forests simultaneously, so the cumulative impact of disturbance events need to be considered when developing management actions[34].

Increased focus on finding solutions

Given the expected rate of change in environmental conditions moving forwards, land managers may need to pre-empt the changes that may occur and implement appropriate management actions for these anticipated conditions[48].

There is increasing call for nature-based solutions to climate change: to address the double needs of biodiversity conservation and carbon sequestration through better management and restoration of natural forests, coastal lands and peatlands (Mori et al. 2021). It's important to recognise that biodiversity is not only something to be conserved, but also a powerful contributor to climate stabilisation[5].

Do more monitoring before or when initiating action

Conservation managers' first instincts have historically always been to minimise and slow the rate of any changes, as human-induced change is the usual cause of species and ecosystem loss. The anticipated extent of climate change impact is inspiring many to call for extraordinary actions, such as translocations. Ecological science is not yet at the point where the results of large-scale human actions, that involve multiple and interacting processes, can always be accurately predicted. If such actions are taken, close, regular monitoring is required to determine whether the desired outcomes are achieved or if the action creates other issues[5]. Monitoring may catch unexpected changes occurring as the complex system is altered, for example due to interactions between multiple factors or to a new agent such as a disease in the system[29].

10.3. Research needs

10.3.1. Forest monitoring

- To facilitate adaptive management, we need improved knowledge of climate change impacts at both the state and local scale (i.e. we are still only predicting the impacts and other unforeseen effects may arise) [15].
- While there are some monitoring programs in Tasmania there is still an urgent need for the establishment of a coordinated state-wide biodiversity monitoring program to gather baseline and trend data (see discussed in (Munks et al. 2009)). Such a program would play a key role in addressing knowledge gaps and inform management decisions in response to emerging impacts of climate change[34].
- Warra Baseline Altitudinal Monitoring Plots were established in the late 1990s to record changes in biodiversity due to climate change (Grove 2004). These plots should be remeasured.

10.3.2. Climate vulnerability/response

- It may be appropriate to review previous efforts to prioritise conservation efforts in light of potential climate change impacts on individual species (as e.g. in Threatened Species Section, 2010)[5].

- More research is needed on the impact of climate change on individual species. One area of particular importance is the timing of reproduction of dependent species (see Simmonds et al. 2020[5]).
- Research/review of the sensitivity of Tasmanian forest communities, by bioregion, to climate change impacts[48].
- Initiating species/provenance trials now in a range of locations.

10.3.3. General ecology

- Species-specific knowledge of life-history and habitat requirements[15].
- Species-specific knowledge of genetic variability, and capacity to adapt to climate change and habitat modification[15,18].
- Climate habitat modelling and mapping of the future distribution of suitable climate for biota, and prioritising mitigative actions[18].
- Improved understanding of ecosystem function. Some species will become extinct under climate change. If too many or key species are lost, the ecosystem function consequences may be very detrimental[5]. For example impacts of removal of specific species from the food chain are untested[15].

10.3.4. Modelling long-term implications

- Landscape scale reporting on changes in habitat extent in relation to forest cover, growth, decline (bushfire and dieback), and loss due to harvesting and clearing, as part of State of Forests reporting. This could include recent developments in mapping current and past fire severity using Landsat satellite imagery – GEE fire severity tool[48].
- Research on future climate scenarios and habitat suitability for high-risk threatened species and habitats[48].

11. Weeds, pests and diseases

The management of weeds pests and diseases is a shared responsibility across all levels of government, industry and the broader community[27]. The *Forest Practices Code* makes the following statements in relation to pests and weeds:

> *Forest practices will be conducted in a manner that meets legislative requirements and minimises the risk of spread of weeds, pests and diseases through effective control measures that have the least risk of adverse environmental impact (p87).*
>
> *Pests, diseases and declared weeds can pose economic and environmental threats and should be managed to minimise these threats. Landowners are responsible for providing reasonable protection to their forests from pests and diseases (p87).*
>
> *Forest practices should not spread weeds, pests or diseases, and measures should be taken to contain outbreaks which arise as a result of the forest practices (p87).*

11.1. Potential impacts

11.1.1. Potential increase in pest and disease outbreaks

Climate change impacts on production forests will include increased plant pest and disease pressure on forests. As conditions become more favourable to pests which favour warmer climates, likelihood of introduction (entry, establishment, and spread) increases (Pinkard et al. 2014) [27], particularly when conditions are also moist[4, 27, 35].

Defoliators are the main pest types in Tasmania. Defoliating insects and stem borers are likely to be favoured by warmer mean temperatures but generally not by heatwaves (Keenan et al. 2020)[35]. Foliar diseases will be favoured by warmer mean temperatures but increasing droughts and lower humidity will likely reduce the abundance and distribution of these pests[35]. Root diseases will be favoured by warmer temperatures and more frequent storm events (Delgado-Baquerizo et al. 2020, Keenan et al. 2020) [27, 35].

However not all pests will increase their damage potential under climate change. Defoliation by leaf beetle *Paropsisterna bimaculata* is likely to reduce with climate change. Similarly, warming due to climate change is expected to lessen the severity of spring needle cast (the most significant disease of radiata pine in Tasmania) (Podger and Wardlaw 1990) [43].

Wardlaw (2010) provides a useful guide for the likely response to climate change of the most significant pests in eucalypt plantations. Concern over the spread of pathogens has also been carefully considered in a review of the threat posed by the introduced pathogen ‘myrtle rust’ (*Austropuccinia psidii*) to Tasmania; another pathogen adapted to the sub-tropics and tropics for full disease expression but extending its range southward in Australia into the cooler climate south-eastern states like Victoria and Tasmania (see Phillips 2021).

There is currently only one disease where there is sufficient information to allow the effect of climate change on the future economic impact to be predicted quantitatively, Teratosphaeria leaf blight (TLB) in young *E. globulus* plantations (Jones 2020). That work predicted an increase in the areas of plantations suffering severe TLB by 2030 but little change after that[43].

Compounding stress on trees

Pest impacts may amplify negative effects of climate change on stand productivity, particular in areas where trees are already stressed such as under warmer conditions in drier areas[16, 35]. For example, stem borers are attracted to stressed trees and may interact with drought stress[35]. Stressed trees can be more prone to dieback, which may result in greater wildfire risk (with associated carbon implications). However, in general our limited knowledge of pest and host responses in eucalypts restricts the reliability of assessment of future impact of insects and diseases on native eucalypt forests[35].

Variable response in weed outbreaks

Weeds can impact production forests by reducing seedling establishment and timber productivity through competition for resources and impacts on natural values in native forests. The occurrence of weeds can increase the control measures required in production forests, which will increase regulatory burden, including compliance responsibilities, especially where new weeds occur as a consequence of climate change range expansion[27].

There is uncertainty surrounding the expected impact from weeds[12] and the degree to which weed species are likely to be impacted by climate change and how those impacts might manifest themselves. However, climate change is likely to favour some weed species and not others[4].

Threats will come from range expansions of both weeds found in Tasmania as well as weed species confined to mainland Australia. Of particular concern are weeds referred to as 'sleepers' that pose a significant risk but are currently limited in extent as environmental conditions are not suitable[27]. CSIRO (Scott et al. 2008) has developed climate scenarios for 41 national alert and sleeper weeds, including 29 weeds not currently recorded for Tasmania, that have the potential to exist or expand in Tasmania given a changing climate. There are numerous other weed species not investigated in the CSIRO project that could have a significant impact in Tasmania[27]. Actions to manage and control these weed species now will prevent significant problems in future years[27].

WeedFutures.net also contains both continent- and state/territory-level spatial assessments to identify regions under both current and future climates where the potential for population establishment and expansion is most concentrated. Weed Futures has also developed a point-based screening tool that rates naturalised but not yet invasive species as having low, medium or high potential for population establishment and expansion now and in the future. This screening tool is designed to assist managers in identifying those species for which detailed weed risk assessment and management are needed[27].

Potential increase in vertebrate pest outbreaks

Vertebrate pests impact production forest by grazing plantations and forests, grazing and stripping juvenile trees and thereby impacting forest establishment and the values in native forests[27].

As with weeds, and probably more so, there is little data or information on the impacts of climate change on vertebrate pests. Improved growing conditions from warmer, wetter seasons will result in good breeding seasons for animals such as rabbits. Where alternative food sources exist, such as grass and palatable herbs, baiting using biocontrols such as calici-virus or poisons such as pindone become less effective. Good breeding seasons lead to high proportions of young rabbits and animals under eight weeks of age which can gain resistance to calici-virus, further reducing effectiveness as those populations transition to older age cohorts. Research in New Zealand has demonstrated that climate change over the past 60 years has reduced the window of time for effective control (Latham et al. 2015). This is largely a product of changes in the efficacy of baiting as seasonally available food increases[27].

Wild deer populations in Tasmania are growing. Population estimates have increased continually from around 8,000 in the 1970s up to 30,000 deer in the mid-2000s. In 2019, the first ever deer census in Tasmania estimated the population to be at least 54,000 and growing at an annual rate of 6.2 per cent (*Tasmanian Wild Fallow Deer Management Plan 2022–27*). As with rabbits, increases in seasonal food availability and suitable habitat will inhibit control and management efforts[27]. These introduced species impact on understorey and ground cover within native forests[34] and are a significant browsing animal feral pest in plantation forests.

11.2. Potential adaptation strategies

11.2.1. Improve forest resilience

Minimise road development and use

Roads often serve as conduits for weeds and diseases entering new areas. Minimising the road network, and public vehicular access to forestry roads will reduce the opportunity for invasion by pests[27].

Regenerate with pest-resistant genotypes/species

Allow for the regeneration of species or seed provenances that would be more resilient to novel pests and pathogens.

11.2.2. Improve pest control management

Development and adoption of a weed/feral pest risk assessment and management approach

Tools available to manage risks posed by outbreaks/epidemics of the main pests and diseases are not expected to change, but the viability and financial returns of a plantation rotation will be assisted by informed analysis of changes in pest/pathogen risk[43]. This could be done by conducting a review of issues and published knowledge on pest animals, weeds and diseases as part of a review of the Forest practices system[27]. This could lead to the development and implementation of an invasive pest strategy and management plan for the forest industry that includes guidance on best practice pest and disease hygiene management[27]. This review may find the need for improved reporting mechanisms, such as a notification process for ‘unusual’ pest/pathogen/disease observations/triggers[48].

The capacity to respond to and manage pests and diseases has recently been improved with the development of a Tasmanian Integrated Pest Management Group (IPMG). This group includes all the main forest growers in Tasmania and provides a forum for a coordinated approach to pest management and forest health surveillance, setting priorities for research and development, the dissemination of information and linkages into national bodies such as Plant Health Australia (PHA) and the Forest Health and Biosecurity subcommittee (FHaB). Current activities of the IPMG include coordinating a tenure blind state-wide invertebrate monitoring program for the plantation hardwood sector and implementing early field trials of a non-lethal vertebrate browsing deterrent, a systemic foliar spray, for forest establishment activities.

Implement pest surveillance measures

To ensure early detection of issues, which would allow timely action, it would be useful to design and implement pest surveillance systems including early alert measures such as sentinel traps[27].

Apply good hygiene measures

It will be important to mandate more rigorous biosecurity measures, such as strict adherence to equipment and machinery hygiene, and restrict materials that may contain contaminants of biosecurity concern[27]. These hygiene measures should be extended to contractors and other third party machinery and equipment operators who may introduce weeds, pests and diseases[27]. The responsibilities of land managers in relation to hygiene include ensuring they don't spread weeds, pests and diseases to neighbouring properties[27].

Prepare response to outbreaks

Timely action on new outbreaks will be an essential part of a management strategy. The preparedness of the industry to respond to biosecurity emergencies will be key[27]. For this to occur, it will be important that the industry know how to identify key invasive species threats[27] and understand their regulatory responsibility. This is particularly important now that the *Biosecurity Act 2019* exists and includes a 'General Biosecurity Duty' which broadens landowners and land managers responsibility in relation to dealing with biosecurity matters[27].

11.2.3. Monitoring

Improve forest health and pest monitoring

Regular monitoring of forest health will be important to detect new outbreaks. New techniques are emerging that could greatly improve the efficiency of monitoring, such as remote sensors, drones and eDNA detection systems[48,27].

It is also important that baselines for priority weed and pest species are identified which will enable assessments of risk and rates of change in relation to population and infestation trends[27]. Greater engagement between the forest industry and Biosecurity Tasmania could help facilitate these actions.

11.3. Research needs

11.3.1. Forest monitoring

- Good, contemporary knowledge and data on the distribution at state and national levels of priority weeds and pest animals is needed. While there is modelling data for individual species, these may not always be relevant to forest industries[27].

11.3.2. Climate vulnerability/response

- Precise data regarding rate of climatic change and associated responses in the forest pest/disease context[27]. This includes up-to-date climate change scenario models for weeds and vertebrate pests[27].

- Greater understanding is needed of the potential pathways of entry to Tasmania of forest pests[27].
- Greater understanding of the impact of pest/pathogen damage on the tree host (survival and growth) (e.g. Smith et al. 2017)
- Greater understanding of the effect of climate on the activity (and therefore damage) of the pest/pathogen (e.g. Pinkard et al. 2010).

12. Factors inhibiting uptake of potential adaptive actions

Some of the factors that may inhibit uptake of potential adaptive actions are listed below.

12.1. Social

12.1.1. Low risk appetite

- There is a risk in adopting new strategies given there is so much uncertainty, which may promote reactive responses to address impacts as they emerge rather than taking proactive approaches.
- For a strategy such as planting climate-adjusted provenances there is a lack of operational exemplars, when compared with the failure of past attempts to introduce ‘tolerant’ species/genotypes to deal with known threats to local species/genotypes e.g. *Phytophthora cinnamomi*-resistant species in dieback areas. There is a risk that climatically-matched provenances (for warmer temperatures) may be very different in other attributes, e.g. rainfall or pest tolerance[43].
- There is a risk of planting new species and the implications for ecological functioning over time. The cumulative impacts of these actions would not manifest for decades if not longer[4].

12.1.2. Lack of social licence

Lack of trust in the industry

- ENGOs are philosophically opposed to native forest management and there is entrenched social distrust of the forestry industry. The community may not trust the concept of managing forests for climate change.
- Planned burns have a bad public image and managers are potentially already under pressure to reduce their use[20].

Lack of public understanding about the issues

- **Fire**: There is a lack of public understanding about fire risks, particularly the risk of large-scale bushfires[17, 29].
- **Carbon**: The public debate lacks an understanding of Tasmania’s fire driven ecology and the full role of forest management versus forest reservation in greenhouse gas mitigation. Over time, Tasmania’s currently carbon rich forests are expected to either burn or transition to rainforest, and it is generally accepted that a transition from wet forest to rainforest will result in a loss of carbon[29] (although this was disputed by one respondent[51]). Thus, the public debate largely focuses on storing carbon in forests and potentially overestimates this benefit[29]. The public debate focuses less on the potential carbon benefits from production forestry, such as from storing carbon in the form of

wood products and substituting carbon intensive resources such as concrete, steel and plastic (Ximenes et al. 2016).[2,29]

Difficulties getting people to change their thinking

- Current thinking is often focused on short term social and economic needs, so tackling climate change issues may require a shift in thinking by government, landowners and land managers. The long time lag between biotically significant climate change related occurrences and the impacts becoming apparent in ecological systems can hinder changes in thinking[28].
- A shift may be required from the industry, to focus less on production and more for other values such as carbon. Within the industry there already exists interest in accounting for carbon in the forests they manage, as it is seen as an economic, social and environmental opportunity[53].
- While for many of the issues outlined there is robust science available, it can be difficult to get people to accept the science. For example, while there is good science supporting the use of thinning forests under some circumstances, thinning may be viewed by the public as an intensification of forest management.
- There is likely to be resistance on ethical grounds to the concept of modifying forest community structure to pre-adapt forests to climate change.

Lack of will from the industry

- Some of the adaptive actions will make management of production forests more complex. Examples include managing rotation age at landscape scales, upgrading biosecurity measures[27], and accurately accounting for the role of forests in carbon accounting[43].
- Industry personnel can be strongly criticised for doing their job, which can make them overly cautious in adopting new techniques or strategies[17].

Lack of will from government

- Reducing legislated sustainable harvest levels will have socio-economic impacts and is likely to be politically unpalatable.
- Governments have a history of avoiding decisions about forests given the polarised views about them[22].
- There is likely to be resistance to setting aside additional pockets of forest for the purposes of landscape-scale biodiversity management aimed at increasing inter-disturbance intervals[18].

12.2. Financial

Cost to the industry

- Changes to silvicultural practices will cost money, meaning the economic return is lower.
- Mechanical management of fuels following harvest activity for fire management will increase the cost of reforestation activities.
- Reducing or eliminating post-harvest burns reduces the efficacy of regeneration methods, which has both economic and environment implications.
- Reducing coupe size means an increase in the logistics of planning operations, with associated costs. There will also be a need for additional roads and more, albeit smaller,

regeneration burns to achieve the same timber yield. There will also be negative impacts on eucalypt regeneration from the increased proportion of edge effects in coupes[2].

Increased cost, but responsible agency uncertain

Many of the suggested adaptive actions have costs associated with them. For some measures it is unclear who should cover these costs, as many are likely to increase operational costs and lower economic returns. Some examples are provided below.

- research into forest tolerances
- forest monitoring
- maintaining a long-term strategic seed bank
- salvage/restoration operations where achieving commercial returns are not the main drivers for the operation.

As no clear agency may be responsible, creative ways of funding the strategies may be required. For example, habitat preservation and restoration might be supported by funds to reduce carbon emissions[5].

12.3. Logistical

Lack of information or knowledge

- Numerous respondents highlighted that knowledge of forest species is limited, particularly in the context of climate change, hindering our ability to develop appropriate adaptive measures. (See research needs above).
- Numerous respondents emphasised the current lack of long-term monitoring of Tasmanian forests. Monitoring is essential for determining when intervention may be required, and for understanding how adaptive measures, or the lack of, are improving the resilience of forests. While costly, technological advances are making this easier to achieve. Some examples of the type of monitoring needed are identified under 'Research needs' above.
- Our understanding of the effectiveness of the proposed adaptive measures is generally limited.
- Lack of knowledge by industry of the key threats posed by climate change and their legislative responsibilities[27].
- One respondent did identify that whilst we can always know more, the key impediment is not knowledge gaps[17].
- Another respondent noted that when the information is available, the process required to take research outcomes into operational practice can be overly onerous and slow [16].

Lack of personnel/expertise

- Insufficient knowledge and know how to conduct reliable risk analysis for inter-rotational decisions[43].
- Limited access to experienced climate modellers to be able develop forecasts of likely pest-related climate change threats[27].
- The *Forest Practices Code* advises that advice be sought from a forest pathologist in the event of extensive unexplained death or decline of trees occurs. For the first time in 50 years Tasmania does not employ any specialist expertise in forest pathology (or forest

entomology) (although there is some expertise at the University of Tasmania). This is at a time when there will be an expected increase in stresses adversely impacting the health and productivity of the forests that will require diagnosis to develop appropriate management actions. The idiosyncrasy of Tasmania's forest health threats compared with mainland Australia will limit the value of bringing in forest health specialists from outside the state on an as needs basis[43].

Lack of opportunity or difficult to implement in practice

- One respondent noted that there are no easy answers on how to address climate change[31].
- Some of the suggested measures to address a particular key issue may have perverse outcomes on other key issues or biodiversity values (e.g. forest thinning, shorter rotation times).
- In terms of fire, there is a lack of practical management approaches to protect standing forests[45]. Opportunities for fuel reduction burning are reducing and the number of days in which bushfires will be difficult to control are increasing[18].
- Supplemental planting can have low success, so trees would probably need to be caged to prevent marsupial browsing[20].

12.4. Policy and Legislation

Legislative requirements, or lack of

- Currently legislated wood volume targets reduce the flexibility the industry has to adapt to climate change, particularly given the decrease over time in harvestable area. One way this could potentially be addressed is by adding much of the Future Potential Production Forests to the area that contributes to the legislated wood volume target.
- There is a lack of landscape or catchment-scale planning policy/requirements[34].
- Gully bottoms are positions in the landscape that are particularly vulnerable to damage from stress events (e.g. Gully dieback, Calder Dieback). Restoration of gully-bottom forests that have suffered significant mortality may be restricted by provisions of the *Forest Practices Code* to protect riparian values. (e.g. 'Burning of native vegetation in streamside reserves and other areas excluded from harvest should be avoided where practicable, unless required as an essential part of hazard reduction or rehabilitation forestry' E1.3 in FPC).
- There is currently no requirement to remediate stands suffering long-term or permanent damage as the result of stress events. In addition, there are no standards that define thresholds of reduced forest values due to dieback and mortality[43].
- There is a lack of procedures and protocols relating to pest incursion response[27].
- There are no clear protocols relating to post disturbance salvage harvesting[46].
- Some potential responses may conflict with existing land use and water entitlements[6].

Work Health Safety

- Some of the measures suggested can cause work health safety concerns. For example, retention of seed trees and mature elements in a harvested area can be logistically difficult and dangerous[20], as can selective harvesting of wet forest[19].

13. Discussion

Quantitative estimates of climate change impact are dependent on the degree of temperature change. The goal of the Paris Agreement is to limit this to below 2˚C, and preferably to 1.5˚C, but current global commitments to address climate change are not sufficient to achieve this. Australia's climate has already warmed on average by 1.44 ± 0.24°C since national records began in 1910, leading to an increase in the frequency of extreme heat and heavy rainfall events. Changes in rainfall and continued increases in the frequency of extreme events such as drought, flooding and fire are predicted (Bureau of Meteorology 2020)[5].

Tasmania's production forests and the associated forest industry is reliant on healthy, productive forests that can produce certified wood that is economically viable to harvest, haul and process, at a supply rate that sustains Tasmanian business operators and ongoing investment[48]. The management of these healthy and productive forest needs to be ecologically sustainable to maintain the associated ecosystem services such as maintaining biodiversity, water catchment regulation, carbon sequestration, and microclimate buffering[48].

Our knowledge of the direct effects of climate change on the health and productivity of production forests (particularly native forests) in Tasmania is very new with most relevant publications less than five years old. Information from the broader literature may not always be appropriate for the Tasmanian context, for example the temperature response shown in Tasmanian wet forests is very much stronger compared with other temperate eucalypt forests on the Australian mainland. Therefore, the relative priorities allocated to dealing with climate change impacts on forest health and productivity may be different to the Australian mainland.

We can however anticipate that the impact of climate change on Tasmanian production forests will be wide and varied. In some instances there will be gradual changes and in others there will be step changes which may lead to alternative stable states.

The industry needs to be flexible and responsive, and not just to tackle environmental issues. Climate change may also result in social changes that exert political pressures on the industry. This may result in new priorities for production forests in the future (e.g. pressure to retain more carbon, burn less) [23], and not all of these can be anticipated.

But climate change is here. Respondents were fairly unanimous in reporting that the impacts of climate change are already being seen and that it is the responsibility of the industry to consider potential management options.

This report provides a range of potential adaptation strategies suggested by the respondents. Many of these are outside the jurisdiction of the FPA or even the forest practices system. Furthermore, there are challenges associated with implementing most of these, not least of which is the uncertainty in the effectiveness or perverse outcomes that may occur. Taking action when faced with such uncertainty is particularly difficult when there are considerable financial and social implications associated with changing management practices. The best we can strive for is to have all relevant parties contributing to the process, to be as informed as possible, and make considered, balanced decisions in a way that informs future decision making.

14. Summary of potential adaptation options

The information provided in this report (and Table below) is an objective and complete synthesis of views on adaptation options received from a wide range of experts. Not all adaptation options identified will be relevant to the forest practices system or supported by the FPA. The next step for this project is to focus on the adaptation options that are relevant to the forest practices system and identify practical and useful enhancements. This is likely to be done by hosting a series of workshops, involving industry practitioners, policy experts and key scientists, to discuss the relevant proposed adaptation options and identify practical and effective courses of action.

Table 2. An overview of the adaptation options suggested from this review, and the pros and cons of adopting the approach.

Issues: Key issues relevant to this action: FH = forest health, F = fire, S = soil, W = water, B = biodiversity, WD = weeds and diseases, C = carbon.

Action: P/R = proactive or reactive, D/I = direct or indirect, S/L = short or long term implications.

Potential benefits: Brief summary of anticipated benefits.

Negative consequences or issues: Potential concerns with the proposed action.

Inhibitors: Potential inhibitors to implementing this action. S1 = low appetite from industry or government, S2 = lack of social licence, C = cost, Lo= logistical, Le = conflicts with legal/policy requirements.

FPS?: Indicates if and how it relates to the FPS.

No.	Adaptation option	Issues	Action	Potential benefits	Negative consequences/issues	Inhibitors	FPS?
A	***Forest regeneration***						
A1	Sow more seed after disturbance	FH, C, F	PIL	- Taller, faster growing, better adapted trees through natural selection - Probably increased economic return	- Increased reforestation cost - Logistically difficult to obtain more seed	C, Lo	Code minimum stocking requirements

No.	Adaptation option	Issues	Action	Potential benefits	Negative consequences/issues	Inhibitors	FPS?
				- Probably increased carbon capture	- Potential increase in risk of water stress for regrowing trees.		
A2	Sow less seed after disturbance	F, W, C	PIL	- Creates lower density stands to reduce water use. - Reduces seed required and associated cost of reforestation.	- Lose productivity and genetic benefits that arise from natural selection when there is excess seed. - Potential negative biodiversity benefits. - Potential but uncertain implications for erosion and fire susceptibility.	S1, Le	Code minimum stocking requirements
A3	Vary the genetic stock of the seed sown	FH, F, W, B, WD, C	PIL	- Potential increased resistance to rising temperatures/ fire/ drought/ pests - Improved forest health pre and post disturbance - Healthier forests provide better habitat for other biota - Improved forest growth and therefore increased carbon capture	- Lose geographic genetic provenancing - Resistance on ethical grounds - Increased complexity of planning to identify suitable seed and monitor results. - Uncertain outcomes (resilience of non-local seed to local pathogens may not be observed for some time). - Potential increase in cost	S2, Lo	Code requirement for local seed use and maintenance of local gene pools
A4	Collect seed from optimum seed provenances	FH, F, W, B	PIL	- Provides opportunities for future action even if use of non-local seed is not	- Increased cost if no plans to use seed	C, Lo	Relevant to the industry but outside the

No.	Adaptation option	Issues	Action	Potential benefits	Negative consequences/issues	Inhibitors	FPS?
				implemented in the short term. - Other benefits outlined above in use of varying genetic stock.	- Other issues outlined above		jurisdiction of the FPA
A5	Plant more climate suitable species	FH, F, W, B, WD, C	PIL	- Potential increased resistance to rising temperatures/ fire/ drought/ pests - Improved forest health pre and post disturbance - Maintain ecosystem function - Healthier forests provide better habitat for other biota - Improved forest growth and therefore increased carbon capture	- Change geographic distribution of forest types and species distributions - Resistance on ethical grounds - Increased complexity of planning - Uncertain outcomes (resilience of non-local plants to local pathogens may not be observed for some time). - Potential increase in cost	S1, S2, Lo	Code requirement for local seed use and maintenance of local gene pools
A6	Collect and sow seed from local areas potentially adapted to warmer temperatures	FH, WD, B	PIL	- Potentially improved forest regeneration and resilience	- Limited areas available to source seed from so rapid action needed	S1	Relevant to the industry but outside the jurisdiction of the FPA
A7	Sow understorey species	FH, F, W, B, C	PIL	- Improved forest resilience through greater diversity - Potential to maintain soil moisture levels through improved shading and thereby keeping	- Potential to exacerbate fire intensity - Significant increase in cost to gather seed	C, Lo	Some threatened species management requires understorey maintenance. No

No.	Adaptation option	Issues	Action	Potential benefits	Negative consequences/issues	Inhibitors	FPS?
				temperatures low and potentially reducing fire risk - Habitat for other biota			current Code requirement unless changing understorey composition resulting in different forest community.
A8	Increase in stored seed	FH, F	PIL	- Ensures adequate seed availability after extreme disturbance such as extensive, high intensity wildfire.	- Expensive - STT store seed but currently there is no responsible agency to store seed for wider use.	C, Lo	Relevant to the industry but outside the jurisdiction of the FPA
A9	Regenerate areas that have suffered dieback and cleared areas that are unused (particularly riparian zones).	FH, F, W, B, C	RDL	- Maintaining forest for multiple values, including biodiversity, carbon capture etc. - Maintain ecosystem function	- Expensive - Potentially complex, as may need alternate silviculture/species to prevent a repeat of the dieback	C, Lo, Le?	Code p88. Code requirement if area has reverted to native grassland (D4.3). Some planning tool implications (e.g. TSA, D4.3)
A10	Minimise soil compaction during forest operations	FH, S, W	PIL	- Reducing compaction will improve soil structure, with implications for forest regeneration, erosion and water storage.	- No practical solution currently identified - Potentially expensive	Lo, C	Code restrictions in some areas (e.g. Code C5, C6, D1, E1).
A11	Review silvicultural practices for native forest	FH, C	PDL	- Potential improved regeneration	- Uncertain weather/climate predictions	S1	Code C1.1

No.	Adaptation option	Issues	Action	Potential benefits	Negative consequences/issues	Inhibitors	FPS?
A12	Adjust reforestation regimes to ensure regeneration	FH, C	PIL	- Improved regeneration - Improved economic return	- Increased complexity of planning - Uncertain weather/climate predictions	Lo	Code E1.
A13	Review the benefits of soil fungal inoculations after intensive disturbance	FH	RIL	- Improved seedling establishment, growth and forest health - Help maintain soil biota	- Unproven benefits - Expensive - Not clear when might be required	C, Lo	Potentially relevant to the industry but outside the jurisdiction of the FPA
B	***Silviculture***						
B1	Forest thinning	FH, W, F, B	PRDL	- Reduce water use of the stand and maintain stream flow - Could be used in a targeted way for areas likely to suffer dieback from water stress. - Promote growth of mature tree form, which is more resistant to fire - Potentially increase forest health and thereby reduce long-term fire risk	- Potential pros and cons for biodiversity - Impractical for widespread adoption - Difficulties in identifying areas that would benefit from this practice. - Residues may increase fire risk in the short to medium term. - Potentially expensive	S2, C, Lo	Planning tool implications, e,g. TSA, swift parrot and other threatened species recommendations
B2	Reduce CBS silviculture	S, F, B	PIL	- Improved social acceptance	- Potentially poorer regeneration outcomes with partial harvest of wet forests	S1, C, Lo	Code C1.1

No.	Adaptation option	Issues	Action	Potential benefits	Negative consequences/issues	Inhibitors	FPS?
				- Improved forest resilience due to maintaining multi-age forest - Improved biodiversity outcomes, including soil biota. - Better maintenance of understorey which is good for carbon, biodiversity and in many situations fire	- Potentially more expensive - Potentially greater safety concerns - Reduced site-scale timber yield potentially leading to harvesting over a larger spatial footprint.		
B3	Reduce post-harvest burns after clearfelling (i.e. use alternative regeneration methods)	F, C, B	PDS	- Improved social acceptance - Reduced carbon footprint - Reduced risk of fire escape - Potentially reduced safety concerns due to the no, smaller or lower intensity regeneration burn	- Poorer regeneration outcomes, including understorey species. - Potentially more expensive - Increased fuel loads following fire increasing fire risk	S1, C, Lo	Meeting the regeneration requirements of the Code E 1.5
B4	Apply alternative silviculture in wet forest that maintains multi-age forest at the stand scale (eg., variable retention)	F, B, W	PIL	- Multi-age forest more resistant to impact of fire in the long term, and provide seed source. - Improved biodiversity outcomes - Potentially reduced fire risk outcomes. - More easily maintain lower temperatures in	- Complexities with identifying a practical, effective, cost-efficient technique (aggregated retention one viable option). - Potential worker safety issues - Potential larger footprint of individual coupes, including snig tracks and roads, to extract the	S1, C, Lo	The max coupe size and coupe dispersal provision of the Code C1.2

No.	Adaptation option	Issues	Action	Potential benefits	Negative consequences/issues	Inhibitors	FPS?
				harvested area and reduce water loss. - Retained mature trees facilitate recolonization of mycorrhizal fungi	same volume of material. - Potentially lower regeneration levels.		
B5	Smaller coupes	F, B, W, FH	PIL	- Create more heterogeneous, resilient landscape - Microclimate in harvested area less impacted - Improved outcomes for streamflow, particularly if coupes are dispersed. - Improved biodiversity benefits for dispersal-limited species. - Likely to achieve greater diversity of species in harvested area more quickly, and diverse forests tend to be more resilient to fire and other disturbances.	- Increased cost of production due to more frequent operation moves. - Logistically more complex, as dispersal requirements would necessitate more operation areas to achieve production targets. - Potentially more roads in the landscape, which are conduits for disease and can impact aquatic systems through runoff and crossings. - Potential negative impact on eucalypt regeneration due to the influence of increased proportion of forest edges.	S1, C, Lo	The max coupe size and coupe dispersal provision of the Code C1.2

No.	Adaptation option	Issues	Action	Potential benefits	Negative consequences/issues	Inhibitors	FPS?
B6	Active plantation management: fertilise, weed suppression	FH, C, WD	PRDS	- Greater crown recovery after insect defoliation - Increased growth rate, promoting more rapid carbon capture	- Impacts of fertilizer on aquatic values.	C	Need to ensure doesn't conflict with plantation provisions of the Code
B7	Prepare salvage harvesting risk assessment protocols and prescriptions	FH, F, B	PISL	- Facilitate rapid, considered response after major fire. - Can assist in regeneration in some circumstances - Ensures all relevant factors are considered, including impact on biodiversity.	- Potential negative impact of salvage logging on regeneration, biodiversity, soils and water.	Lo	CFPO currently to provide guidance
C	***Landscape management***						
C1	Minimise deforestation	C, B, W, S	PDL	- Reduces long-term carbon emissions - Maintains more habitat for biodiversity. - Forests help maintain soils and regulate water flow.	- Increased cost, potentially for compensation - Potential conflict with landowners - Difficult to cease deforestation entirely due to infrastructure management and safety concerns.	Le, C, Lo	PNFEP and relevant Code and planning tool requirements
C2	Plant more trees	C, B, W, S	PDL	- Increased carbon storage - Potential benefits for biodiversity, water and soils. - Increased wood resource.	- Need to ensure areas being planted are appropriate (e.g. not native grasslands). - Limited areas available for planting.	Lo	Many plantings will require an FPP so need to ensure Code and planning tools

No.	Adaptation option	Issues	Action	Potential benefits	Negative consequences/issues	Inhibitors	FPS?
				- Improved resilience of farm enterprises.	- Lack of knowledge about the FPS.		account for this activity.
C3	Minimise habitat loss	B	PDL	- Maintains more habitat for biodiversity.	- Increased cost - Increased logistical considerations - Decreased area for wood production	Le, C, Lo	PNFEP and relevant Code and planning tool requirements
C4	Maintain older trees and forest patches	B,C,F, FH	PIL	- Create more resilient forests less prone to drought and fire. - Numerous biodiversity benefits - Carbon storage. - Source of seed.	- Logistically difficult in some silvicultural systems. - Loss of production forest available for meeting wood volume targets.	Lo, C	Code and planning tool (TSA) requirements as well as *Forestry Act* wood volume quotas.
C5	Increased coupe dispersal	W, F, B	PDL	- Young forest potentially at higher risk of burning, so minimizes highly flammable areas within close proximity. - Helps maintain water flow in the catchment as younger trees can use a high level of water. - Reduces risk to dispersal limited taxa and species with limited ranges.	- Increased logistical considerations - Potential increase in the road network	C, Lo	Code and planning tool (TSA) requirements
C6	Reduce harvest rotation intervals	FH, B, C, F	PIL	- Maintain higher productivity (and carbon capture)	- Change in product size potentially reducing economic profit.	S2, C	May have implications for some TSA

No.	Adaptation option	Issues	Action	Potential benefits	Negative consequences/issues	Inhibitors	FPS?
				- Young forests may be less sensitive to warmer temperatures, so maintain forest health. - Greater opportunity for genetic adaptation under rapidly changing climate.	- Less time available for biodiversity recruitment - Lack of social license. - More young forest potentially increasing fire risk and impacts on biodiversity		recommendations that mention rotation times in terms of reducing impacts on threatened species – hollow user recommendations (e.g. masked owl, swift parrot)
C7	Increase harvest rotation intervals	F, W, B, C	PIL	- Older trees more resilient to fire - Older forest has different biodiversity values to younger forest. - Longer term carbon storage. - May help maintain species that are maladapted to emerging climate	- Less area available to harvest each year	C, Le, Lo	*Forestry Act* wood volume quotas
C8	Limit the amount of forestry occurring in a landscape	W, F, B	PIL	- Catchment management to maintain water flow - Less younger forest within close proximity, potentially reducing fire risk - Reduced on-ground fuel loads - Reduced impact on biota - Reduced fire risk	- Logistically more complex - Potentially issues finding enough resource - Potentially limiting area available for harvest	Lo, C	Code Section D2 and C1.2. *Forest Management Act* 2013 – Section 16 – Wood Production Supply

No.	Adaptation option	Issues	Action	Potential benefits	Negative consequences/issues	Inhibitors	FPS?
C9	Coordinate catchment management	W, B	PIL	- More effective catchment management for maintaining water flow.	- Logistically difficult to coordinate multiple agencies and private landowners. - No structure in place	Lo, C	Relevant to the industry but outside the jurisdiction of the FPS.
C10	Greater protection to high-risk catchments	W, B, F	PIL	- Improved stream flow management in high risk areas. - Improved management of important values in high risk areas.	- No process identified - Increased cost of reducing land available to harvest	Lo, C	Relevant Code provisions for soil and water and biodiversity.
C11	Increase habitat connectivity	B	PIL	- Facilitates movement of species throughout the landscape. This is important for dispersal limited species, and may be particularly important in areas subject to disturbance such as fire or forestry.	- Increased cost (loss of harvest area) - Logistically difficult in multiple-tenure regions.	C, Lo	Code D4 WHS requirements and those relevant to landscape and catchment planning (D2.1)
C12	Do climate smart forestry	C	PDSL	- Transparent incorporation of carbon management into forest management planning and systems. - Reduced carbon emissions and increased carbon storage.	- More complex strategic planning	Lo	Has the potential interactions with the *Forest Management Act*, the *Forest Practices Act* and various elements of the Code.

No.	Adaptation option	Issues	Action	Potential benefits	Negative consequences/issues	Inhibitors	FPS?
D	***Protect important values***						
D1	Identify and map at-risk or important values	FH, B, W, S	PIL	- Facilitates greater protection, by multiple agencies, of important values (e.g. fire refugia, threatened communities etc.).	- Cost	Lo, C	Code planning considerations
D2	Additional protection measures for rare or high value species and habitats.	B, FH	PDSL	- Improved conservation of special values. - Protection is already provided under the FPS but this could be more precautionary in some cases, or could involve protecting species for non-forestry threats such as predation	- Cost and logistics of managing additional threats such as predation. - No clear agency responsible.	C, Lo	Code biodiversity provisions Planning requirements and planning tools (TSA)
D3	Reserve areas of old forest and climate vulnerable forest communities	F, B, FH, C	PIL	- Old forests provide important values for a range of biota - Improved social acceptability - Improve resilience of the landscape to fire	- Reduced area available for harvest - Reserving wet forest may over time result in lower carbon storage.	C	Relevant Code provisions (eg., in B1) and FPS planning tools
D4	Increased reservation/retention of at-risk values (e.g. climate refugia)	FH, B, S	PIL	- Greater protection of at risk values, including genes, species, soils, structural stages	- Reduced area available for harvest	C, Lo	Code planning requirement

No.	Adaptation option	Issues	Action	Potential benefits	Negative consequences/issues	Inhibitors	FPS?
D5	Improve protection of damp/cool refugia and riparian zones	FH, B, W	PDL	- Wider SSR would maintain cooler creeks for in-stream biota - Riparian zones can provide habitat for a disproportionate array of species, so is efficient for conserving biodiversity - Maintains areas less likely to be impacted by fire - Promotes landscape connectivity	- Reduced area available for harvest - Increased complexity of planning - Cost	C, Lo	Code catchment and SSR provisions (D2) and planning tool recommendations
D6	Maintain refugia and areas available to source seed	FH, F, B, C, WD	PDL	- Maintains options for genetic adaptation to fire, drought and increased temperatures - Facilitates long-term maintenance of forest health.	- Reduced area available for harvest - Increased complexity of planning	C, Lo	Code provisions D4.2 (e.g. WHC) and TSA recommendations
D7	Widen riparian buffers	FH, B, W	PDL	- Wider SSR would maintain cooler creeks for in-stream biota - Riparian zones provide habitat for a disproportionate array of species, so is efficient for conserving biodiversity - Maintains areas less likely to be impacted by fire	- Reduced area available for harvest - Increased complexity of planning	C, Lo	Code SSR provisions (D2.1)

No.	Adaptation option	Issues	Action	Potential benefits	Negative consequences/issues	Inhibitors	FPS?
				- Refugia under increasing drought and fire conditions - Help maintain water quality			
D8	Review adequacy of current measures for minimising sediment movement	S, W, B	PDS	- Will help ensure measures used are adequate for changes in rainfall patterns. - Will help minimize soil erosion	- Degree of change in rainfall intensity may be uncertain	S1	Relevant to the FPS. Various Code requirements
D9	Improved protection of features retained from harvest	FH, B	PDS	- Greater conservation of important features	- Increased complexity of planning - Increased cost	C, Lo	Relevant Code provisions for protection of retained areas
D10	Facilitate expansion/ recruitment of habitat	B	PIL	- Improved species conservation outcomes	- Lack of resources - Lack of responsible agency - Lack of understanding of how to achieve this outcome	C, Lo, Le?	Generally outside the jurisdiction of the FPS. However, may be relevant for some TSA recommendations.
D11	Facilitate species translocations	B	PDL	- Improved species conservation outcomes	- Lack of resources - Lack of responsible agency - Lack of suitable translocation sites - Lack of knowledge	C, S2, S1, Lo, Le?	Outside the jurisdiction of the FPS.

No.	Adaptation option	Issues	Action	Potential benefits	Negative consequences/issues	Inhibitors	FPS?
D12	Increase broader efforts to reduce threats to biodiversity	B	PDSL	- Improved species conservation outcomes	- Lack of resources - Lack of responsible agency - Lack of understanding of how to achieve this outcome	C, Lo	The FPS aims to reduce potential impacts on biodiversity but this point specifically refers to options outside the jurisdiction of the FPS.
D13	Triage species management			- Practical solution to an impossible situation.	- Loss of species. - Lack of social license.	S2, Le	Conflict with threatened species legislation.
E	***Roads***						
E1	Maintain roads for improved access for firefighting	F, S, W, B	PIL	- Facilitates rapid fire suppression	- Negative impact of roads on biota - Increased sediment input into streams	C	Code B4
E2	Mimimse road development and use	F, S, W, B	PIL	- Minimises impact on biota - Limits movement of weeds and diseases - Minimises sediment input into streams from unsealed roads - Reduced cost	- Spatially concentrates harvesting, which may increase fire risk - Reduces ground-based firefighting options	F, Lo	Relevant to the industry and related to landscape planning but outside the jurisdiction of the FPA (but see Code B3)
E3	Improve roading in catchments at risk of flooding	W	PIL	- Minimises sediment input into streams - Improves logistical access to operations after flooding	- More expensive in the short term - Uncertainty about where to deploy or how	S1, C, Lo	Roading provisions of the Code

No.	Adaptation option	Issues	Action	Potential benefits	Negative consequences/issues	Inhibitors	FPS?
				- Maintains infrastructure in the long term at potentially lower cost	necessary the measures are		Code planning requirements – Consideration of ‘At-Risk catchments. Planning tool for identification of ‘At-Risk’ catchments
F	***Disturbance – Fire***						
F1	Manage landscape availability of fuel	F, B, C	PDL	- Lower fire risk across the landscape - Fewer fires reduces carbon emissions	- Uncertainty about how to achieve this, silviculture? Fire? Mechanical removal? - Increased cost - Risk to biodiversity through reduction in CWD	S2, C, Lo	Relevant to the industry but outside the jurisdiction of the FPA
F2	Increase fuel reduction and/or ecological burns	F, B, C	PIL	- Lowers fire risk across the landscape - Fewer fires reduces carbon emissions - Increased regeneration of some species	- Cost - Increased logistical planning - Narrowing window for conducting burns - Less effective for reducing fire risk under catastrophic conditions - Impact some ecosystem functions and some taxa	C, Lo, S2	Relevant to the industry but outside the jurisdiction of the FPA

No.	Adaptation option	Issues	Action	Potential benefits	Negative consequences/issues	Inhibitors	FPS?
					- Uncertain benefit from carbon perspective		
F3	Adjust timing and scale of planned burns	F, B, C	PIL	- Reducing the scale of burns may provide a patchier landscape that ensures habitat retention for many species.	- Increased logistical considerations - Increased cost - Narrowing window for conducting burns - Reducing scale of burns may mean more residue onsite, potentially increasing wildfire risk.	C, Lo	Code C2
F4	Mechanical removal of fuels	F, B, C	PIS	- Lower fire risk across the landscape - Fewer fires reduces carbon emissions - Could use the residue for other purposes (e.g. biofuel)	- Risk to biodiversity through a reduction in CWD - Increased cost - Increased complexity of planning	C, Lo, S2	Relevant to the industry but outside the jurisdiction of the FPA
F5	Green fire breaks	F, B, C	PIL	- May reduce fire risk across the landscape - Fewer fires reduces carbon emissions - Increases heterogeneity of some landscapes	- Depending on the type of fire break, may involve forest conversion which would increase carbon emissions and reduce habitat for biodiversity - Increased complexity of landscape planning - Potentially loss of area available for production	C, Lo	Relevant to the industry but outside the jurisdiction of the FPA

No.	Adaptation option	Issues	Action	Potential benefits	Negative consequences/issues	Inhibitors	FPS?
					- Increased cost associated with managing these breaks		
F6	Improve detection of bushfires	F, C	PDSL	- Decreases response time to attend fires, improving opportunity to control fire.	- Expensive	C, Lo	Relevant to the industry but outside the jurisdiction of the FPA
F7	Improve firefighting capacity	F	PDS	- Improved opportunity to control fire, limiting size.	- Expensive	C, Lo	Relevant to the industry but outside the jurisdiction of the FPA
F8	Have one coordinated firefighting organisation	F	PIS	- Increased efficiency of firefighting effort	- Logistically impractical given current partners involved with firefighting	C, Lo	Relevant to the industry but outside the jurisdiction of the FPA
F9	Do nothing	FH, F, S, W, B, WD, C		- Easy - Given the uncertainty of the impact of climate change, or the best actions, this may be the safest course. - If the fires don't burn now, they will later, not trying to control them may help promote resilience for future conditions.	- Potential negative impacts on multiple values - No learning achieved to prepare for future conditions/ requirements/actions - Out of control fires puts communities and infrastructure at risk	S2, C	No action so no implications for FPS.

No.	Adaptation option	Issues	Action	Potential benefits	Negative consequences/issues	Inhibitors	FPS?
F10	Use more forest residue	F, B, C	PIS	- Financial offset to reducing fuel loads across the landscape - Using residue for biofuel should decrease global carbon emissions.	- Social acceptability - Needs to be done well or poses risk for species dependent on CWD	S2, Lo, Le?	CWD provisions Code D4 and some TSA recommendations
G	***Disturbance – Weeds, pests and disease***						
G1	Development and adoption of a weed/feral pest and disease risk assessment and management approach	WD	PIS	- Forward planning will maximise the probability of reducing pests and weeds before they establish.	- Cost	C	Relevant Code provisions Code planning requirements Associated planning tools Code monitoring requirements
G2	Implement pest surveillance measures and adopt new technologies	WD	PIS	- Facilitates a rapid response to pest outbreaks, meaning actions are more likely to be effective	- Cost	C	Relevant to the industry but outside the jurisdiction of the FPA
G3	Develop and apply an industry standard best practice guide for hygiene management	WD	PIS	- Decreases likelihood of pest species establishing or spreading	- Cost - Can be logistically difficult to do effectively	C, Lo	Hygiene measures applied via the Code and planning tools (e.g. Phytophthora technical note).
G4	Prepare response to outbreak	WD	PIS	- Decreases likelihood of pest species establishing or spreading	- Cost	C, Lo	Relevant to the industry but outside the

No.	Adaptation option	Issues	Action	Potential benefits	Negative consequences/issues	Inhibitors	FPS?
					- Lack of effective response options		jurisdiction of the FPA
H	***Carbon***						
H1	Reduce use of fossil fuels	C	PISL	- Decreases the role of the industry as a carbon emitter, thereby helping reduce the impact of climate change	- Cost - Motivation - Lack of practical options	C, Lo, S1	Relevant to the industry but outside the jurisdiction of the FPA
H2	Improve carbon monitoring	C	PIL	- More accurate understanding of the role of forestry in Tasmania's carbon balance - Improves local knowledge of the role of forests to feed into carbon accounting, and allows mitigative actions to be identified.	- Has the potential to change the direction of forest management	S1	Relevant to the industry but outside the jurisdiction of the FPA
H3	Improve carbon accounting	C	PIS	- More accurate communication of the role of forestry in Tasmania's carbon balance - More accurately reflects the relationship between forestry and fire.	- Makes the calculations substantially more complex - May require ignoring some widely accepted practices (eg. how forest harvesting and wildfire are accounted) - Puts more onus on Tasmania to take action, which increases planning complexity and costs	C, Lo, S1	Relevant to the industry but outside the jurisdiction of the FPA

No.	Adaptation option	Issues	Action	Potential benefits	Negative consequences/issues	Inhibitors	FPS?
H4	Develop forest management policies and practices to better manage carbon	C	PIL	- Increased likelihood of reducing the carbon footprint of the forest industry, thereby helping reduce the degree of climate change.	- Puts more onus on forest industry to take action, which increases planning complexity and costs - Lack of political will. - May require changing or eliminating wood volume targets	S1, Le	Relevant to the industry but outside the jurisdiction of the FPA
H5	Produce carbon friendly products	C	PIL	- Help reduce the overall carbon footprint of the forest industry. - Potential for different financially lucrative options. - Potentially more socially acceptable.	- Uncertain of the success of potential options - Lack of appetite for change - Currently have legislated wood volume targets so may be more difficult to achieve	S1, C, Lo, Le	Outside the jurisdiction of the FPS.
H6	Adopt a price for carbon	C	PIL	- Help promote widespread management of carbon emissions.	- Lack of political will - Lack of social acceptability	Le, S2	Relevant to the industry but outside the jurisdiction of the FPA
I	***Adaptive management***						
I1	Adjust sustainable yield calculations and harvest levels	F, B, W, C	PIL	- Increases flexibility of the industry to respond to current conditions (e.g. wildfire) and markets. - Allows other adaptive actions to be implemented (e.g. catchment	- Concern by the industry that wood supply is not guaranteed - May impact profits of timber companies	Le, S1, C	*Forest Management Act 2013* – Section 16 – Wood Production Supply

No.	Adaptation option	Issues	Action	Potential benefits	Negative consequences/issues	Inhibitors	FPS?
				management, heterogeneous landscape).	- Currently have legislated wood volume targets and contractual agreements		
I2	Transparently include bushfire-related loss in timber modelling	F, C	PIL	- Gives more realistic idea of product likely to be available over time, facilitating more appropriate future planning. - Greater social acceptability.	- Makes it difficult to achieve wood volume targets - High uncertainty in expected loss due to bushfire	C, Lo	*Forest Management Act 2013* – Section 16 – Wood Production Supply
I3	Improve forest monitoring	FH, F, W, B, WD, C	PIL	- Increases knowledge base from which to inform management decisions. - Facilitates adaptive management with potential long-term benefits for a range of values.	- Expensive - Benefits not necessarily apparent immediately	C, Lo	Forest Practices Act and RFA
I4	Plan forestry at multiple spatial and temporal scales	F, W, B	PIL	- Facilitates adoption of different strategies at appropriate scales. - Facilitates cross-tenure management.	- Logistically difficult - Increased complexity of planning - Potentially increased cost associated with increased complexity - Benefits not necessarily apparent in the short term	S1, C, Lo	Code planning provisions

No.	Adaptation option	Issues	Action	Potential benefits	Negative consequences/issues	Inhibitors	FPS?
I5	Apply an adaptive and collaborative management approach	FH, F, S, W, B, WD, C	PIL	- Facilitates appropriate and effective management of multiple values.	- Increased complexity of planning - Increased cost - Requires expertise in relevant field	S1, C, Lo, Le	Code doesn't allow flexibility on a number of issues
I6	Have a flexible, and responsive management system	FH, F, S, W, B, WD, C	PIL	- Facilitates appropriate and effective management of multiple values.	- Increased complexity of planning - There are delays between validating information and implementing it - Requires relevant expertise	S1, C, Lo, Le	Code doesn't allow flexibility on a number of issues
I7	Increased focus on finding solutions	FH, F, S, W, B, WD, C	PIL	- Facilitates appropriate and effective management of multiple values.	- Solutions are not always readily available - There can be a substantial time lag between identifying issues and then solutions	C, Lo	Adaptive management approach of the FPS

15. Appendix 1: Questionnaire sent to participants

Reviewing how the forest practices system should adapt to climate change

The FPA have developed this form as a template that you can use when providing information on how the Tasmanian forest practices system could adapt to climate change. It has been intentionally designed to be short in order to not be unduly onerous. However, it is only a suggested format, and people may submit a more detailed or lengthy report, or may request an ‘interview’ instead. The idea is that each ‘expert’ will fill out this template for each of the key issues (outlined below) they have expertise in. However if more convenient, you can cover multiple key issues in the one document. The ideas expressed in this document will be explored in more detail, with the practitioners during the workshops.

The seven key issues identified as relevant to the Tasmanian forest practices system are outlined below, with some examples of major sub-topics provided for some key issues. There may be considerable overlap between some of these key issues. If you think there are other key issues not covered below, please either contact the project manager, or submit a report on that key issue.

Please feel free to forward this form to any other researchers or practitioners you think may be able to assist us in our review.

<u>Key issues</u>

1. Carbon
    a. Storage
    b. Emissions
2. Forest health
    a. Impact on growth and health of existing plants
    b. Impact on plant recruitment (flowering, seed production, germination and establishment, window available to do regeneration burns)
    c. Changes in mortality (e.g. windthrow, dieback)
    d. Genetic stock
    e. Non-forested vegetation health
3. Wildfire
    a. How to promote recovery after fire
    b. Salvage logging
    c. Promoting recovery of flora and fauna after fire
    d. Fuel loads and forestry interactions
4. Soils
    a. Changes in soil nutrients, carbon, moisture and productivity
    b. Changes in soil biota
    c. Increased erosion from extreme weather
5. Water
    a. Stream flow
    b. Changes in flow regimes (peak and low flows)
6. Biodiversity
    a. Threatened species
    b. Non-threatened species
7. Weeds and diseases

Expert name: ____

Current or relevant previous roles: __________________________________

Contact Email/Phone number:____

Date:__________________

Key issue(s) to which this report applies: _______________________________

With regards to this key issue, please outline the impact(s) that you think climate change may have that is relevant to Tasmanian production forests, or the Tasmanian forest industry. Include information on any changes seen to date, and changes that are expected to be seen in the future.

Please indicate the context of your response above in terms of (a) the time frame you are considering, (b) the spatial scale at which you are framing your response and (c) the rate of change you are anticipating (e.g. step change or gradual change over hundreds of years).

Please provide some ideas about how the forest industry could adapt in response to the impacts outlined above.

Identify any factors that may inhibit adoption of recommended strategies

Identify any key and relevant knowledge gaps

Please provide the details for any important scientific references relating to this topic.

Additional comments

16. Appendix 2: People who provided a response in this review

Listed below are all the people who provided written and/or verbal feedback.

- Billie Lazenby
- Brad Potts
- Carolyn Maxwell
- Clare Hawkins
- Craig Nitschke
- David Bowman
- Dean Williams
- Gary Sheridan
- Hans Ammitzboll
- Jamie Furlaud
- Jamie Kirkpatrick
- Jayne Balmer
- Jon Marsden-Smedley
- Julianne O'Reilly-Wapstra
- Karen Richards
- Kirsten Adams & Bryce Graham
- Luke Kelly
- Marie Yee
- Mark Hovenden
- Mark Neyland
- Mark Wapstra
- Martin Moroni
- Micah Visoiu
- Michael Askey-Doran and Mike Noble
- Mike Ryan
- Nathan Bindoff
- Oberon Carter
- Patrick Baker
- Patrick Lane
- Paul Fox-Hughes
- Peter Harrison
- Peter McIntosh
- Peter Volker
- Phil Smethurst
- Rod Keenan
- Sarah Munks
- Sarah Russell
- Shaun Suitor
- Simon Grove
- Steve Leonard
- Sue Baker
- Tim Brodribb
- Tim Wardlaw
- Tom Baker
- Todd Walsh
- Tom Fairman
- Vanessa Thompson

17. Appendix 3: Biodiversity Expert Review references to climate change

Below are comments listed in the Review of the biodiversity provisions of the Tasmanian *Forest Practices Code* in 2009 that relate to climate change.

- Recommendation 13: The FPA should collaborate with other relevant bodies, including DPIW, FT, PFT and private land stakeholders, to prepare a discussion paper on its role in the provision of strategic level planning, with a view to informing government on the need to clarify roles and responsibilities across government for the strategic level conservation of biodiversity outside of reserves. This paper should include discussion on strategies and processes to deal with emerging issues such as the effects of climate change. (chapters three and four). P13
- Climate change: Climate change is a key issue in the planning and management of biodiversity conservation and there is uncertainty about the exact nature and magnitude of future change. A landscape approach to managing forest biodiversity, modified as the panel recommends, should provide some insurance to allow biodiversity and ecological processes to respond to changing conditions. P17.
- The panel notes that the issues of air pollution, climate change and fire all potentially impact on biodiversity in ways that are not addressed by the current *Forest Practices Code*. The panel recommends that the *Forest Practices Code* overtly and formally consider these issues for inclusion in future reviews of provisions where needed. P65
- Climate change: The *Forest Practices Code* currently does not mention climate change. In recent years, climate change has emerged as a key issue in biodiversity management and planning, though uncertainty still remains about the exact nature and magnitude of future climate change. A landscape approach to biodiversity management provides a precautionary and optimal approach allowing species and ecological processes to respond to any changing conditions. This particularly applies to linkages that maintain large contiguous habitats or that enable maintenance of ecological processes, especially across a range of environmental gradients. Future biodiversity planning and management should be informed by scientific understanding of likely implications of future climate change, as identified in the National Biodiversity and Climate Change Action Plan 2004–2007 (NRMMC 2004). P70–71
- The panel recommends that the FPA prepare a discussion paper on its role in the provision of strategic level planning, with a view to informing government on the need to clarify roles and responsibilities across government for the strategic level conservation of biodiversity outside of reserves. This paper should include discussion on strategies and processes to deal with emerging issues such as the effects of climate change. P80–81
- Management of genetic resources: The *Forest Practices Code* has some generic provisions related to the importance of maintaining genetic resources. Use of local seed provenances is encouraged and specific mention is made of the issue of eucalypt hybrid events: ‘consideration should be given to the protection (e.g. by buffering) of native forests, particularly reserves, from incursion by adjoining plantation species’. However the protection of localised examples of threatened species and communities should also be considered, as must the management of genetic diversity within species at the landscape level. For example, some of the associated forest practices planning tools currently deal with glacial refugia, which have high degrees of genetic endemism.

However, these alone will be unlikely to adequately cover the strategic for maintenance of genetic diversity for issues such as climate change. P85

- Research priorities: Long-term ecological research on natural processes, the effects of forest management and climate change, and long-term monitoring at established sites.
- The policy documents all explicitly recognise the importance of good scientific process for the determination of biodiversity conservation needs in a wood production forest environment. Accordingly, the panel suggests the following scientific knowledge objective and sub-objectives: identify species or ecological communities at risk from climate change. P108
- In summary, the panel endorses the need recognised in the above instruments and documents for strong R&D and monitoring programs in the forest practices context for biodiversity conservation. The primary research and monitoring needs for the FPA to fulfil its charter for biodiversity conservation are to increase understanding for management in the following areas: climate change. P109
- To retain genetic diversity at a local and land - scape scale. It is important to buffer species and communities against abiotic and biotic environmental threats and change and maintain evolutionary processes. Geographically or ecologically outlying populations are of particular significance due to their divergence through drift or adaptation to atypical environments. Genetic diversity at all spatial scales is important for the adaptive response to climate change. P124
- The proposed secondary objective is: To complement the existing CAR reserve system by applying measures (taking a risk spreading approach and ensuring consistency with effective fire management, silvicultural practice and safety requirements) to:….. maintain capacity for adaptability of the elements of biodiversity in the face of climate change. P125
- Secondary objective: Maintain capacity for adaptability of the elements of biodiversity in the face of climate change. Manage landscapes for greater resilience to cope with increased average temperatures and changed water and fire regimes. Adaptation of forest trees and associated organisms will depend on factors such as (i) in situ genetic diversity and gene flow within and between species (ii) ability to disperse to more suitable habitat Climate change is likely to see an upslope shift in species ranges and patterns of adaptation. The drier, lower, eastern portion of the island is believed to have been a major forest refuge during glacial periods. Eucalypt endemism and genetic diversity is higher in this area which is likely to harbour important biodiversity elements for future environments. The maintenance of migration routes for forest species through habitat connectivity is an important consideration. The lowland coastal forests of the island are an important interface between terrestrial and marine ecosystems, that requires particular attention. Performance indicator: Number of forest taxa reported to be adversely affected by climate change Proportion of the area of native forest exhibiting declining health due to climate change factors (e.g. drought) in each bioregion. Number of enhanced migration corridors P141–142.

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